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The Role of Physiology in the Development of Golf Performance

Mark F. Smith

Department of Sport, Coaching and Exercise Science, University of Lincoln, Lincoln, UK

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Abstract

The attainment of consistent high performance in golf requires effective physical conditioning that is carefully designed and monitored in accordance with the on-course demands the player will encounter. Appreciating the role that physiology plays in the attainment of consistent performance, and how a player's physicality can inhibit performance progression, supports the notion that the application of physiology is fundamental for any player wishing to excel in golf. With cardiorespiratory, metabolic, hormonal, musculoskeletal and nutritional demands acting on the golfer within and between rounds, effective physical screening of a player will ensure physiological and anatomical deficiencies that may influence performance are highlighted. The application of appropriate golf-specific assessment methods will ensure that physical attributes that have a direct effect on golf performance can be measured reliably and accurately. With the physical development of golf performance being achieved through a process of conditioning with the purpose of inducing changes in structural and metabolic functions, training must focus on foundation whole-body fitness and golf-specific functional strength and flexibility activities. For long-term player improvement to be effective, comprehensive monitoring will ensure the player reaches an optimal physical state at predetermined times in the competitive season. Through continual assessment of a player's physical attributes, training effectiveness and suitability, and the associated adaptive responses, key physical factors that may impact most on performance success can be determined.

Golf, as a sporting pursuit, requires the player to undertake a range of physically demanding movement patterns throughout the course of play.[1] The player must be able to cope with stressors that affect the physiological process of movement within various situational and environmental contexts during each competitive round. Depending on the specific requirements encountered on-course, the golfer must optimally organize and create complex swing movements repetitively in order to maximize scoring opportunities.[2] While the need for such invariance in technique across all swings for a number of key discrete golf swing positions has recently been demonstrated,[3,4] dynamical systems theory does suggest that high-level performance in sports like golf would benefit from some degree of functional variability in non-key swing positions.[5] Such findings reveal that the summation of movement requires a multifactorial approach to performance, which encompasses physical, mental, tactical and technical attributes.[3] Energetically, golf necessitates the interplay between biochemical, neurological, endocrinological and muscular functioning, allowing for the execution of each individual shot.

The aim of this review is to elucidate the important role physiology plays in the development of the golf player. By describing the demands the golfer encounters throughout the course of play, the characteristics inherent in proficient players can be examined and compared with those of lower ability. By further examining factors that contribute to optimized physical status of the player, strategies can be developed to assist both player and coach in the enhancement of this fundamental aspect of golf success. Finally, to assist coaches, trainers, players and scientists in identifying and monitoring progress to maintain motivation and advance performance throughout training and competition, the evolvement of a physical-development framework for performance enhancement is presented. Where gaps in the golf-related literature exist, evidence from the wider sports science literature is included to advance applied knowledge and understanding.

It is not the intention of this review to discuss or outline in detail the technical or biomechanical aspects of the swing characteristics; therefore, interested readers are directed to comprehensive reviews by Hume et al.,[1] Jorgensen,[6] and Peary and Richardson.[7] Nevertheless, an understanding of how the physical aspects affect overall player success is examined, allowing for the development of more multidisciplinary approaches to player movement optimization and competition performance maintenance.

For the purposes of this review, original and review articles from 1988 to the present were considered by the author. Prior to this date, it was viewed that golf-related research lacked methodological suitability. A literature search of conference proceedings was performed (e.g. World Science Congress of Golf-Science and Golf: 1990–2008), SportDiscus®, MEDLINE and ScienceDirect databases, and the internet (i.e. Google Scholar), using the keywords 'golf', 'physical fitness', 'exercise' and 'physiology' to identify relevant articles. Manual searches were also performed by searching through article reference lists.

1. The Paradox of Golf: Why does One Need to be Physically Fit to Play Golf?

Golf is perceived as a relatively gentle game in which the physiological demands are not particularly demanding. From a less-informed perspective, success in golf is seen to be more about the technical, tactical and mental aspects rather than the physical. By viewing the range of physiques and associated fitness levels golfers exhibit, one can begin to see why this view has developed. The physical fitness of the golfer, historically, has not appeared to be of that much importance. Consider, however, the repetitive acceleration and deceleration of the body during the golf swing. Combined with repeated compression and rotational torsion of the spine, and shearing around the joints, one can begin to identify that from a global position, the physiological demands of golf seem no different from that of walking. From a skeletal and muscle functioning perspective, however, substantial physical stress is applied. Taken that over 2000 swings are being performed by the tournament professional through practice and competition each week,[8] and up to 300 powerful movements per practice session,[9] plus competitions lasting up to 4 days in demanding environmental conditions, one can begin to appreciate the importance of physical fitness to golf performance.

With the advent of golf science, technological changes and players looking for an edge over their competitors, the addition of physical conditioning training into a golfers practice schedule has revealed the importance of the physically fit golfer. With growing evidence suggesting that the physical fitness of the highly proficient player is somewhat different from that of a lower ability player,[10] attention has been given to the role physical fitness and physical conditioning can play in developing golf performance.

2. Macro Aspects of Golf Performance

From a physical perspective, golf can be viewed from two levels. From a 'macro' aspect of performance, operationally defined as all physical movements that occur outside the executed golf swing, the ability to walk the course with minimal impact on the mental and/or technical proficiency of the player promotes optimal execution of individual shots. The time taken to complete a round and the movement demands in between each shot can affect the physical stability of the player throughout the course of play.[11] In studies that have measured total walking distance over the course of 18 holes, the actual distance covered in relation to measured course length was on average 38% longer, equating to an extra 2.32 km travelled.[10-12] Taking this into account, the 'macro' aspects of golf performance, although not physiologically demanding, can have a meaningful impact on the physical condition whilst performing each swing.

3. Micro Aspects of Golf Performance

Remaining in a stable state throughout these in-between periods ensures the performer is capable of attaining the desired outcome through the 'micro' physical aspect of performance. This is operationally defined as all physical movements that occur during the execution of the golf swing. Occurring in <1.3 seconds to impact,[13] the physiological chain of events that bring about the dynamism of the golf swing, irrespective of the shot type, characterizes the main acute physical demands acting on the golfer. Given that a highly proficient player will shoot around 70–76 shots per round, 91–99 seconds is all that is required to perform at this micro level of movement. Given that round times can extend up to 5–6 hours on the professional tours, around 0.5% of time during a tournament round will be spent executing golf shots. Despite such a small amount, the importance of this defines the success or failure of the player.

4. Role of Physiology

To achieve consistent performance throughout a round of golf, one might consider the value of a stable physiological state. Accordingly, a player/coach would consider a training programme and nutritional strategy that promotes such a stable physiological state within a round and across days. An understanding of such a state and how it affects movement potential will provide the coach with a valuable awareness as to the importance of correct preparation and maintenance throughout player development.

Appreciating the role that physiology plays in the attainment of technical excellence and how a player's physicality can inhibit performance progression supports the notion that physiology should be a fundamental area of focus for any player wishing to excel in golf. In viewing player optimization from a multidisciplinary perspective, the role of physiology should be seen as equally important as other contributing factors. Technical, tactical, mental and life skills will affect and be influenced by the physiological status of the player.[3] For the coach or player who does not acknowledge and integrate physiological aspects of performance into their development plan, the chances of reaching optimal movement capabilities will not be realized.

Although, in the broadest of sense, physiology of movement is concerned with the understanding of how physical activity alters biological systems during and immediately after movement, as well as in response to physical training,[14] wider aspects contribute to a more holistic appreciation of the impact this area has in understanding how golf performance can be optimized. Anatomical characteristics, body composition, movement measurement and evaluation, nutrition, ergogenic aids, mechanisms of fatigue and environmental stresses[15] are factors that to one extent or another affect technical aspects of movement, tactical and mental approaches within and between play, player development and training, and management of physical status. Viewed from a whole-body physiological perspective, performance in golf requires operation of all functional and system components of the golfer (figure 1). An appreciation of these will facilitate a more complete understanding of the true physiological parameters influencing performance achievement.

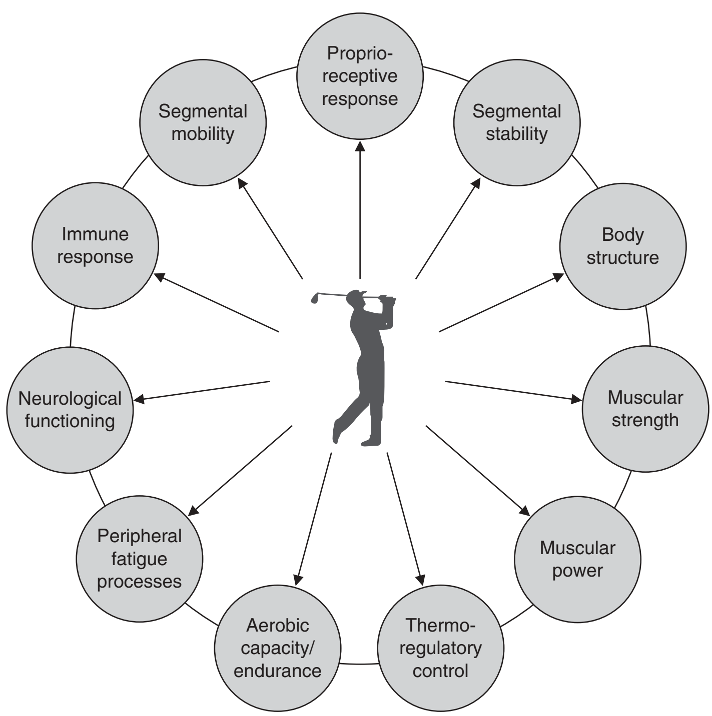

Fig. 1. Physiological factors that can affect successful golf performance.

It is the application of such multidimensional approaches to player enhancement, combining technical, tactical and mental skills with physiological aspects that will bring about the desired change in the player and lead to an increased chance of repeatable success.

5. A Multidimensional Approach to Golf Improvement

The synergistic relationship between equipment, technique and body enables the golfer to repetitively coordinate the body to produce the golf swing movement. The relative contribution of each of these components will impact on the attainment of an optimized golf swing and consequentially influence competitive success (i.e. lower scores). From the coach's perspective, an understanding as to the relative importance of each component will allow for effective evaluative measures of the golf swing and the identification of movement limitations that may ensure corrective advice appropriately focuses on the necessary impingement to swing enhancement. From a sport scientist and researcher's viewpoint, establishing causal links between each component and performance outcome can provide evidence as to how performance can be improved through effective intervention strategies.

A framework in which golf performance can be divided into components provides the coach and player with an elementary entry point into the more detailed factors influencing both decision making and movement. Existing models examining the physical components of golf primarily focus on aspects relating to muscular strength, flexibility, cardiovascular and body conditioning.[16-19] Attention drawn to preparatory practices tends to neglect, however, the importance of maintaining a stable state whilst competing. It is the achievement of such state throughout the course of play and the ability to minimize deterioration through appropriate management techniques that may improve on overall scoring success. How a player's physical state is managed during play could therefore have significant effect on optimal golf performance in the latter stages of the round or competition.[20] As illustrated in figure 2, prior to play, the golfer's objective is to ensure that aspects relating to aerobic capacity, strength and conditioning, flexibility, podiatric and optometric considerations, dietary habits and injury management are factored into the overall player plan. Once competition begins, the objective shifts to the maintenance of such state. Taking into consideration environmental conditions and the consequential impact these will have on physical performance, the player must select appropriate strategies in order to minimize performance disruption.

The relative importance of each of these will obviously change within and between players, and – dependent on experiences, expectations and aspirations – development focus should follow an individualized approach to player improvement. Such a holistic approach to optimized performance development is widely accepted as a means of reaching performance potential,[15,21] and extensive holistic practice ensures that peak form can be attained in all aspects of performance. Aspects relating to physical, tactical, technical, life and mental skills have evolved our understanding of golf as a complex dynamic activity that encompasses a multidisciplinary approach to player development.[20]

In determining the relative importance of such components within a multidisciplinary approach to player development, it must be established which elements underpin the development of successful golf performance. In achieving this, it must firstly be recognized that success in golf should be viewed with some subjectivity. Despite skill development and optimization of the player, the determination of scoring success will to some extent be influenced by equipment, weather and course conditions.[22] Nevertheless, the achievement of consistently successful scoring in golf should be built on the premise that objective aspects of performance must be the primary focus of any player or coach in attaining a consistent, efficient, repeatable golf swing that brings about the desired outcome. Ultimately, to execute such skill and achieve the required goal the player must exhibit exemplary performance in all aspects of their game. Deficiency in one or more components will be detrimental to overall scoring

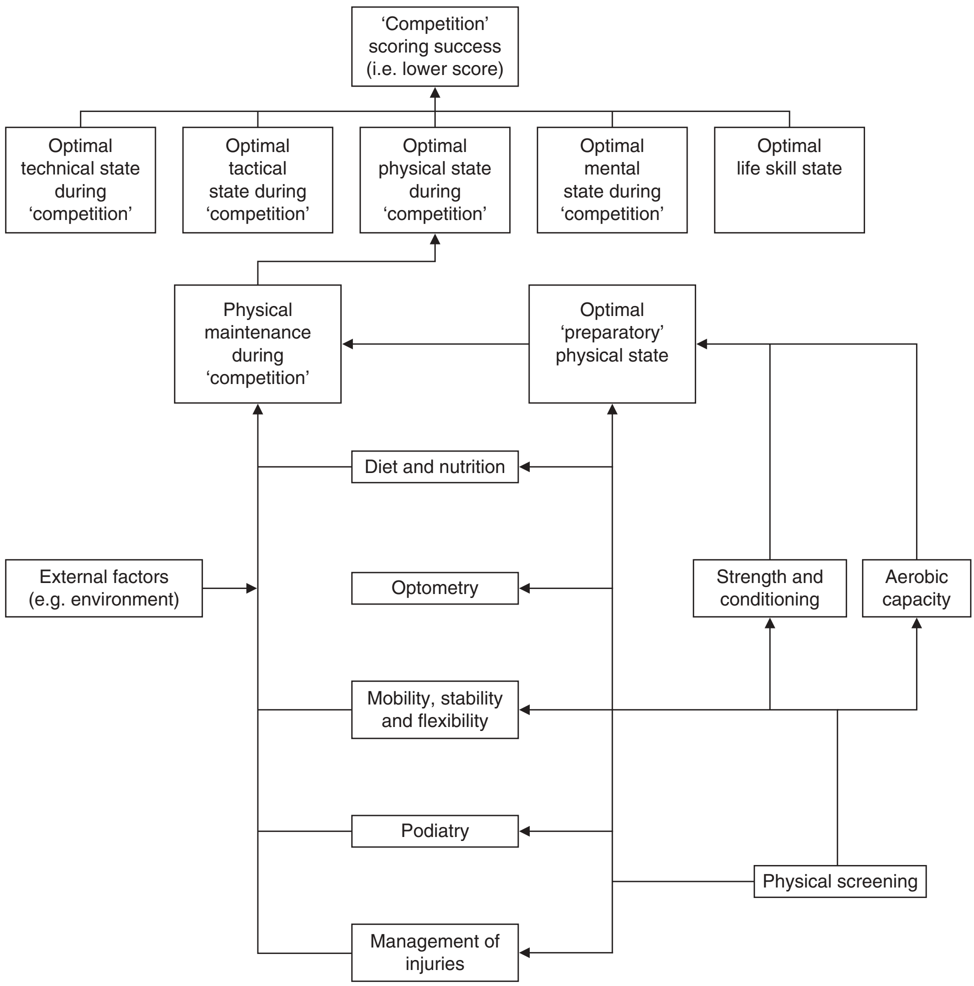

Fig. 2. A multidisciplinary approach to golf performance enhancement.

success and consequently diminish optimal performance achievement and maintenance.

6. The Physical Requirements of Golf

Dynamics of the golf swing are to a large extent dictated by the anatomical and physiological make-up of the body (figure 1). Swing types are usually governed by what the player can and cannot do with their bodies during static and dynamic positioning. The achievement of optimized golf performance could therefore be compromised by player physicality, affecting the attainment of required swing mechanics in bringing about successful ball displacement. Genotypic attributes – such as sex, maturational status, limb characteristics (e.g. limb length and limb symmetry) and stature – in combination with physiological indices – such as muscular activation patterns, muscle balance and symmetry, muscle fibre type, strength, flexibility, mobility, coordination, proprioception and somatotype – will dictate static postural characteristics and dynamic body movements. For example, rotational aspects of the hip, shoulder and spine through the swing have been shown to affect club-head speed and consequently ball distance.[23-25]

The inter-relationship between energy system utilization, thermoregulatory processes and fluid balance will further affect the player's condition when performing movements throughout the course of play.[26] Performing in a varied range of conditions will also contribute to altered physical status and further compromise swing dynamics. Environmental factors will have considerable impact on the physiological status of the body.[26] Temperature,[12,26] altitude[27] and course topography[28,29] will alter internal conditions, and the player must have the appropriate strategies to ensure that any potential physical change is minimized and does not manifest in detrimental swing performance.

6.1 On-Course Physical Demands

It is not unusual for elite players to cover distances in excess of 10 km during the course of play[30] and, dependent on course topography and altitude changes, additional demands will be placed on the golfer.[29,31] Furthermore, influences such as unpredictable weather conditions, speed of play and length of match combined with temporary internal physiological alterations, caused by stress response[20,32,33] and player confidence,[34] will affect strategic approaches taken during competition. Throughout the course of the round and across days, the player must attempt to stabilize physiological status. Developed during preparation, the player must ensure that for each shot played, their physiological state remains as close to their starting point as possible without any undue fatigue, for it is the player who can minimize such decrement that will remain in an optimized state for the longest. As illustrated in table I, the 'macro' energetic demands of golf highlight the relatively low cardiorespiratory requirements needed by the golfer during the course of play. Considering the multidisciplinary approach to golf performance (figure 2), this consequentially will have a significant impact on optimized scoring success.

6.1.1 Cardiorespiratory Demands

The cardiorespiratory challenges that arise from golf are not considered intense,[39] and reflect the low energetic nature of golf performance. Due to ease of measurement and cost associated with monitoring heart rate response throughout the course of play, findings of past research highlight the cardiovascular stress response (table II). On-course playing conditions over a variety of course terrains indicate relatively low cardiovascular stress response when compared with other activities.[15] Exercise intensity expressed as a percentage of predicted maximal heart rate ranges from 52.1% to 78.7%, with absolute values of 95[1] to 137 beats/min.[28] The higher relative and absolute values, however, relate to playing only three selected holes on a hilly course and therefore may not reflect

Table I. Reported 'macro' energy demands of playing 18 holes of golf on an undulating course. All data relate to walking the course whilst carrying a full set of clubs

Performance variable	Value/range	Reference
$\dot{V}O_2$ (mL/min/kg)	22.4	35
$\dot{V}O_{2max}$ (%)	35–46	36,37
Heart rate response (beats/min)	95–120	11,12,20,31
HR_{max} (%)	52.1–67.4	11,12,20,31
Ventilatory response (L/min)	50.8	35
Respiratory exchange ratio	0.87	35
Lactate response (mmol/L)	0.8–1.1	38
Total energy expenditure (kcal)	960–1954	35,36
Energy expenditure (kcal/min)	6.0–11.8	35,36
Distance covered in excess of course distance (%)	27–72	11,12,30,35

HR_{max} = maximal heart rate; **$\dot{V}O_2$** = oxygen uptake; **$\dot{V}O_{2max}$** = maximal $\dot{V}O_2$.

Table II. Mean absolute and relative heart rate (HR) response measured during on-course golf performance

Study (year)	No. of subjects	Handicap	Sex	Age (y)	No. of holes	Absolute HR (beats/min)	HR_{max} (%)[a]
Hayes et al.[11] (2008)	7	12.5	M	50	18	95	54.8
Peterson[12] (2008)	13	≤7	M	24.1	18	111	58.4
McKay et al.[20] (1997)	15	3.8 ± 0.5	M	22.5	18 (practice)	100	52.1
	15	3.8 ± 0.5	M	22.5	18 (competition)	117	61.0
Magnusson[28] (1999)	9	?	F	46.9	3	122	69.5
Magnusson[28] (1999)	10	?	M	48.9	3	137	78.7
Stauch et al.[29] (2008)	30	?	M/F	53.5	18	113	66.1
Burkett et al.[31] (1999)	10	5–20	M	24	18	120	62.9
Sell et al.[35] (2008)	1	?	M	43	18	120	67.4

a Predicted HR_{max} = 206.9 – (0.67 * age).

F = female; **HR_{max}** = maximal HR; **M** = male; ? indicates not specified.

cardiovascular response throughout an entire 18-hole round.[28] McKay et al.[20] found a 17% increase in absolute heart rate response between a practice and competition round, possibly reflecting a psycho-physiological stress response during tournament play.

In a study by Sell et al.,[35] the cardiorespiratory response to three playing conditions was determined over 18 holes. Average oxygen uptake ($\dot{V}O_2$) and expiratory volume for walking whilst carrying clubs was higher (22.4 mL/min/kg; 50.8 L/min) than when walking with an electric trolley (18.3 mL/min/kg; 44.2 L/min) or riding on a cart (15.6 mL/min/kg; 33.1 L/min). The respiratory exchange ratio was highest in the walk-carry condition (0.87) compared with the others (0.63 and 0.71, respectively). Murase et al.[36] found that middle-aged men walking an 18-hole course functioned at a mean exercise intensity corresponding to 35–41% maximal $\dot{V}O_2$ ($\dot{V}O_{2max}$). These findings seem comparable with others,[37] who have reported maximal aerobic capacity of 46 ± 2.6% $\dot{V}O_{2max}$ in amateur golfers.

From a non-locomotive movement perspective, increases in blood pressure (diastolic, systolic and mean arterial pressure) and cardiac output have been reported during fast isokinetic movement.[40] With movement characteristics similar to that encountered throughout the swing, findings suggest the presence of acute cardiovascular stress during the golf swing. Furthermore, findings from non-golf-related research that investigated cardiovascular stress response to force-velocity properties of dynamic movement found increases in mean arterial pressure, indicating that individuals with a greater muscular strength and speed of movement might respond with larger acute cardiovascular disruption.[41] Measuring inter-beat interval during three different shot types, Cotterill and Collins[42] found there to be an increase in the duration of inter-beat intervals prior to shot execution, indicating a decrease in heart rate response. Interestingly, all golfers showed a greater increase in inter-beat interval for shots using a putter compared with the driver. A more recent study[43] found elite golfers, when compared with experienced and novice players, showed a more pronounced deceleration in heart rate immediately prior to a putt and a greater tendency to show a respiratory pattern of exhaling immediately prior to movement. Findings indicate an inherent pre-shot execution pattern that has a cardiorespiratory impact and may be linked to conscious alterations in breathing frequency and cardiac response.[43]

6.1.2 Metabolic and Hormonal Response

Indicators of metabolic and hormonal response prior to, during and after golf competition are suggestive of enhanced physiological and psychological stress that may affect effective shot-making. Lactate response during the course of 18 holes of play has been recorded around 0.8–1.1 mmol/L – indicative of resting levels.[38] Following the completion of 18 holes of golf, blood glucose levels have been shown to decrease with a concomitant increase in fatty free acids.[36] Broman et al.[44] noted that following the completion of an 18-hole course, mean blood glucose levels fell on average by 20%, 10% and 30% in young (27 ± 5 years), middle-aged (50 ± 7 years) and older men (75 ± 4 years), respectively.

Dobrosielski et al.[37] reported elevated levels of adrenaline (epinephrine) and noradrenaline (norepinephrine) throughout the course of play compared with baseline levels; however, there was no change in the ratio throughout the competition. Cortisol has been linked to the homeostatic regulation of various psychological and physiological processes, such as emotional control and metabolic support.[45] During performance, cortisol levels, which reflect physiological coping, have been shown to alter through a round of golf. McKay et al.[20] revealed that cortisol levels were significantly higher throughout an 18-hole competition compared with a practice round (5.8 ± 1.6 vs 2.4 ± 1.1 nmol/L, respectively). Further findings revealed levels for both practice and competition reduced significantly throughout the 18 holes. Supported by more recent evidence,[46] it has also been noted that non-elite players (handicap >7) tend to have a higher, although non-significant, cortisol level prior to, during and after competition compared with elite players (handicap <3). This may indicate more developed psychological coping strategies and advanced training programmes to deal with competitive stress. Wang et al.[47] found that in elite golfers competing in a national tournament, recorded levels of cortisol and dehydroepiandrosterone sulphate, which has been associated with the magnitude of psychological stress,[47] both fell significantly and remained lower in those who failed to make the cut, when compared with those players who did.

6.1.3 Musculoskeletal Demands

Musculoskeletal functioning during the golf swing has been extensively studied and reviewed.[1,2] It must be observed that with in excess of 2000 swings being performed by the tournament professional during practice and competition each week[8] and with up to 300 powerful movements per practice session,[9] such musculoskeletal involvement requires muscular stability and strength to withstand complex loading patterns. These include shear,[48] compression[48] and axial torsional loads.[49] Such rapid directional changes that require alternating force production necessitates the activation of trunk and axial muscle groups at specific periods throughout the movement. With the most active muscles during the swing being located in the torso, shoulder and hip,[2] the musculoskeletal demands acting on the body require structural and physiological stability and strength.[10]

6.1.4 Energy Expenditure

Total calorific expenditure for a round of golf has been determined for a range of conditions.[35] It has been estimated by way of portable cardiorespiratory measures during play on a hilly course that walking whilst carrying a bag expended 1954 kcal (11.8 kcal/min) covering a distance of 8.69 km in a time of 2 hours 46 minutes. This was reduced to 1527 kcal (9.2 kcal/min) for walking with a trolley (total distance was 7.89 km in a time of 2 hours 46 minutes. However, Murase et al.[36] found average calorific values of 960 kcal following 18 holes of golf, which equated to 6.0 kcal/min. Estimating oxygen demands and extrapolating energy expenditure, however, may have underestimated actual energy requirements.

6.1.5 Nutritional Requirements

With a single round of golf taking between 2.5 and 6 hours – depending on course terrain and distance, playing partner(s) and the nature of competition – effective nutrition ensures energetic requirements of play are met and hydration status maintained.[50] This is further affected when issues relating to ambient conditions,[12] optimal dietary provision surrounding travel to and from training and competition,[51] specific physique requirements[1] and the impact that excess weight may have on movement skills[52] are taken into account.

The onset of mental and physical fatigue through inadequate and/or inappropriate dietary practices will have a significant impact on the player's ability during performance. Research conducted by Derave et al.[53] illustrates that suboptimal hydration strategies will compromise functional ability, in particular dynamic postural stability. This will inevitably jeopardise dynamic movement capabilities and lead to diminished optimal performance success. It has been identified that golfers in a dehydrated state significantly underestimated distances to the pin, when compared with a euhydrated state (Newell et al., unpublished observations). Correct nutritional choices can mean the difference between causing and preventing low energy, hunger and muscle fatigue during performance. Low blood sugar, as found following 18 holes of golf,[44] can easily contribute to or cause a lack of focus, irritation, impatience and poor decision making.[15]

6.1.6 Impact of Fatigue on Decision Making

In planning an approach to stabilize physical performance during competition, the coach and player must recognize that a key strategy is to minimize both local muscular and central fatigue development. Such onset of fatigue will impact, first, on the ability to select the right shot type and, second, the execution of the swing. Low level fatigue similar to that which might be encountered during a round of golf has been shown to impact negatively on decision-making accuracy.[54] During a decision-making test, which involved selecting the correct performance outcome from a range of scenarios, accuracy scores following sustained light exertion were significantly lower compared with pre-test and high-exertion performance. In light of these observations, small decrements in decision-making accuracy for the golfer may occur during extended matches in unfavourable conditions or across days within a tournament.

As outlined by Tripp et al.,[55] in complex kinetic chain movements, such as the golf swing, localized muscle fatigue caused by both acute and prolonged muscular activation can have a negative effect on how the body moves. Upper extremity muscle groups have been shown to reorganize muscle activity patterns during the onset of fatigue, thereby combating overload of specific muscles and minimizing fatigue.[55] Such reorganization of multiple joint angles or muscle firing patterns may therefore compensate for fatigue of one muscle or synergistic muscles throughout the movement. Despite this, such mechanisms, in preventing the onset of fatigue, may actually alter the complex coordinative segmental patterns of movement necessary to bring about required golf swing. The involvement of additional muscle(s) to offset fatigue may play a detrimental role in swing mechanics and therefore, considering the small margins of error involved in precise impact achievement, even slight fatigue may compromise outcome success. Such a notion is supported by evidence that has highlighted the effect fatigue – induced by maximal dynamic movements, similar to that encountered during golf – has had on skilled movement performance.[56] Davey et al.[56] noted that following sustained movement, which resulted in peripheral fatigue, the ability to perform a dynamic tennis shot was diminished. The authors postulated that with the onset of fatigue comes an accompanying decline in skill, manifesting through poor timing, body alignment and segment coordination.

7. Physical Attributes of the Golfer

With a growing empirical research base characterizing the physical attributes of the high-performance golfer and the application of such data to player enhancement strategies, a greater acceptance and value of applied physiological research into golf is emerging (table III). As a consequence, an understanding of the physiological nature of golf and the profiling of the player from a functional movement point of view has grown in popularity. As a consequence, this has provided the technical coach with a much clearer evaluation of movement limitations and areas of development, with evidence revealing the significance of such data collected from these assessments for overall performance achievement. With the focus on the physical aspects of mobility, stability and strength at movement points activated during the golf swing,[63] the elucidation of the physiological differences between highly proficient and less able golfers provides a starting point from which physical scientific support can commence. By understanding the qualities exhibited by the player and determining the areas of weakness, effective implementation can be integrated into the routine development plan.

Table III. Anthropometric and physiological characteristics measured during golf-related research

Study (year)	No. of subjects	Handicap	Sex	Age (y)	Mass (kg)	Height (cm)	HR_{max} (beats/min)	$\dot{V}O_{2max}$ (mL/min/kg)	Body composition
Magnusson[28] (1999)	10	?	M	48.9	66.9	?	176	33.2	?
Magnusson[28] (1999)	9	?	F	46.9	82.4	?	182	38.5	?
Burkett and von Heijne-Fisher[31] (1998)	5	≤8	M	25.6	73.4	178.0	?	?	?
Burkett and von Heijne-Fisher[31] (1998)	5	8–13	M	22.4	73.6	176.0	?	?	?
Pheasey[57] (2008)	1	Elite	F	?	65.7	162	198	45.7	23.9%
Kosendiak et al.[58] (2007)	8	≤8 (mean, 5.8)	M	16	74.9	179.5	?	?	20.8% (18–27%: BIA)
Keogh et al.[59] (2009)	10	Low (i.e. 0.3)	M	22.9	76.8	180	?	?	10.0% (4-site)
Keogh et al.[59] (2009)	10	High (i.e. 20.3)	M	27.8	73.5	177	?	?	12.5% (4-site)
Kras and Abendrroth-Smith[60] (2001)	56	Amateur	M	17	?	?	?	?	10.2%(3.2–23.2%: 3-site)
Russell and Owies[61] (2000)	?	Low (i.e. ≤5)	M	?	?	?	?	?	95.1 mm (7-site)
Russell and Owies[61] (2000)	?	Low (i.e. ≤8)	F	?	?	?	?	?	121 mm (7-site)
Duncan et al.[62] (2006)	148	Elite (i.e. ≤3)	M/F	18	75.6	180	195[a]	48.7 (predicted)	17.3%

a Predicted $HR_{max} = 206.9 - (0.67 * \text{Age})$.

BIA = bioelectrical impedance analysis; **F** = female; $\mathbf{HR_{max}}$ = maximal heart rate; **M** = male; $\mathbf{\dot{V}O_{2max}}$ = maximal oxygen uptake; ? indicates not specified.

7.1 Aerobic Fitness

With golf imposing a relatively low cardiorespiratory demand,[35,36] it is of no surprise that reported $\dot{V}O_{2max}$ values for golfers are lower than other more demanding endurance-based sports,[14] and similar to that of healthy active adults.[15] Values of 45.7 mL/min/kg have previously been reported in elite female golfers when assessed on a bicycle ergometer,[57] whilst others reported values as low as 33.8 mL/min/kg in middle-aged amateur golfers[28] during treadmill assessment.

7.2 Anaerobic Capacity

With the complete golf swing lasting less than 2 seconds,[13] the measurement of anaerobic capacity has been made in an attempt to reflect energy demands of the movement. Conducting a Wingate sprint assessment on a group of elite junior golfers, Kosendiak et al.[58] reported peak power values of 722.3 W (9.64 W/kg), similar to those recorded by athletes from wrestling, athletics and football.[58] Although such assessment has little direct transfer to the golf swing movement, the measurement of anaerobic fitness as part of a wider physical screening programme can offer indices for global physical fitness and response to training.

7.3 Functional Strength

Strength, especially around the hips, pelvis and lower back, is essential for optimal performance in golf.[10,59] Every effective swing has a starting point or setup, which places the golfer in an optimal position to execute the repeatable, efficient movement through impact. Such interface between the ground and the body allows for stabilization in which kinetic energy can be created and utilized. Throughout the initiation of the movement, such forces are built from the ground upwards with the kinetic linkage between upper and lower body segments triggering movement, bringing about hip to shoulder rotational difference.[58] With higher velocity of movement within these areas, comes a greater need for strength of the activated musculature.

Assessing the torso, shoulder and hip strength of golfers across three proficiency levels (low, handicap <0; mid, handicap 1–9; high, handicap 10–20), Sell et al.[10] found that low handicap players recorded significantly greater ($p<0.05$) right hip abduction, right hip adduction, left hip abduction, right torso rotation and left torso rotation strength than both mid- and high-handicap groups. Furthermore, strength recorded for right shoulder internal rotation, right shoulder external rotation and left shoulder external rotation was significantly higher ($p<0.05$) than the high-handicap group. Findings reveal that highly proficient golfers, who are able to generate higher club head speed and create a greater 'X' factor stretch,[64] have greater spinal and shoulder strength, especially of the rotor cuff. This has particular importance with regard to injury prevention and joint stabilization considering the high prevalence of shoulder- and cervical-related injuries recorded in professional players.[65] Through the measurement of golf-specific functional rotational strength (i.e. golf swing-specific cable wood chop), Keogh and colleagues[59] found that low-handicap golfers (0.3 ± 0.5) had significantly greater ($p=0.001$) strength than high-handicap players (20.3 ± 2.4). Findings also revealed significantly greater ($p<0.05$) strength measured by way of a non-golf-specific 1 repetition maximum bench press. When functional rotational strength and bench press strength were correlated with maximum club head speed, findings revealed a significant positive relationship ($r=0.706$, $p<0.01$; $r=0.500$, $p<0.05$; respectively). With evidence being collected from mainly male populations, further research is warranted across age groups and between sexes in order to develop more individualized training programmes based on differing physiological characteristics.

7.4 Flexibility and Balance

Throughout the golf swing, individuals are required to attain positions that require good flexibility and balance. The inability to attain and maintain movement positions within and between swings through poor range of motion can lead to ineffective movement patterns and unwanted shot outcomes. Assessment of global lower back and hamstring flexibility (i.e. sit-and-reach) in a range of golfing abilities[21,60] has revealed greater range of motion in more able players. Furthermore, measures of shoulder abduction and shoulder external rotation have shown greater flexibility in players with a lower handicap.[59,66,67] Confirming previous observations, Sell et al.[10] recorded significantly greater range of motion for right shoulder extension, right shoulder external rotation and left shoulder extension in highly proficient players compared with lower ability levels. Moreover, when evaluating lower limb and torso flexibility for the first time, findings revealed that the lower handicap players (handicap <0) had significantly greater right hip extension, left hip flexion and right torso rotation than the less proficient players (handicap 10–20).[10] These findings have been further reinforced by Keogh et al.,[59] who observed measurable differences in follow-through trunk rotation (degree of rotation) and backswing trunk rotation (degree of rotation).

Little evidence is currently available that has investigated flexibility across sex or age groups. What primitive empirical data that have been presented, suggest that for similar playing standards, torso rotational flexibility appears to be comparable in males and females.[68] However, considering anatomical and physiological differences between sexes and the impact age has on physical status,[39,69] such findings are far from conclusive and further methodologically rigorous investigations utilizing larger samples are necessary.

For optimal execution of each shot, balance in the form of good tempo and rhythm, free from jerky unnecessary movements, allows for controlled, posturally stable maintenance of the centre of mass around the base of support.[1] Studies examining balance characteristics have utilized fairly basic assessment methods to establish differences between playing ability. Evaluating a number of high-school junior golfers, Kras and Abendrroth-Smith[60] measured the duration of a one-legged stance with the player's eyes closed (stork test). Findings revealed a wide dispersion of times ranging from 4 to 60 seconds (mean 28.4 seconds). Sell et al.[10] applied the same assessment, advancing further by measuring anterior/posterior and medial/lateral ground reaction forces for both legs with eyes open and closed. It was noted that low-handicap players (<0) had a significantly greater balance on the right leg under the eyes-open condition for the medial/lateral and anterior/posterior force compared with higher-handicap players.

7.5 Podiatric Factors

In storing kinetic energy during the swing, a firm foot-to-ground interface must occur, as different foot pressure patterns will affect swing success.[69,70] Equally, once the kinetic energy is released and unwinding begins, an effective foot-to-ground relationship will promote a stable base for rotational movement back to ball impact and beyond. Forces building up through the foot therefore have an all-important part in the ability to bring about the desired movement in other body segments.[69] With such shear forces permeating through the feet during all aspects of the movement, an appreciation of the podiatric attributes of the golfer may have a positive impact on performance.

From an anatomical perspective, lower extremity length discrepancies have been reported to influence the biomechanical aspects of dynamic movements.[71] As Perrin[71] notes, the spine, pelvis and lower extremities are all involved in compensating for leg length differences. Key compensatory mechanisms that would impact on the golf swing include pelvic tilt, lumbar scoliosis, knee flexion, plantar flexion and supination. Structural aspects relating to physical shortening of unilateral lower limbs, which may be congenital or caused through trauma, and functional unilateral discrepancies, potentially caused as a result of shortening of soft tissues, ligament laxity, hyperpronation or lumbar scoliosis.[71] Such physical deformities may manifest through habitual golf posture,[72] which will mechanistically alter swing dynamics. The prescription of appropriately fitted orthotic insoles, for example, may provide a corrective measure that in part improves balance, proprioceptive symmetry[73] and dynamic mechanical efficiency,[74] off-setting leg length inequalities.

There are currently no empirical data in the golf-related literature that document the prevalence of leg length discrepancy or foot pathology in golfers. What is known is that leg length inequality is common, with 23% of the general population having a discrepancy ≥1 cm.[75] This means that nearly one in four golfers will have leg length differences that may be impacting on swing performance. The prevalence of leg length inequality requiring a corrective device, such as that of an orthotic device, has been reported as one in 1000;[75] however, many may be unaware and therefore are not reported. McRitchie and Curran[76] found that the use of orthotic inserts by golfers who had previously been diagnosed with underlying foot pathology reported less pain and significantly enhanced foot posture throughout the golf swing. Stude and Gullickson[77] noted that with the addition of orthotic shoe inserts over a 6-week period to correct for structural abnormalities, measures of club head velocity increased by up to 7%, equating to an extra 15 yards (~14 m). Furthermore, a reduced level of fatigue was reported that led to a more consistent golf swing. Further research is warranted to evaluate the prevalence of leg length inequality within the golfing community, so more specific corrective programmes and associated treatments can be delivered specifically to this population.

7.6 Visual Function

The decision of shot type and the following execution of the swing are primarily dependent on inflowing visual information about the target and surrounding areas. Interpretation of environmental cues will inform internal decision-making processes, thereby bringing about movement pattern requirements.[78] Considering this, visual acuity and ability to perceive contextual differences (i.e. shades of green, gradient changes, flag distances) should be viewed as important physical attributes of the golfer. Compromised visual function may influence the processing of external information and result in performance inconsistency. Anecdotal evidence by leading PGA (Professional Golfer's Assocation) tour players,[79] supported by scientific research,[80] underlines the need for regular evaluative visual examinations throughout any player's physical development plan. Optometric assessments to establish functioning – such as visual acuity (ability to resolve detail in a high contrast area), depth perception (simultaneous two-eye processing of subtle visual information over distances) and contrast sensitivity (ability to resolve detail under reduced contrast conditions)[80] – will provide informative descriptive data as to areas of player weakness. As outlined by Coffey et al.,[80] all these measures are trainable and have been shown to differ across performance abilities. Professional tour players, for example, have been shown to have significantly better visual functioning in all three areas compared with amateur and senior players. Findings reveal, therefore, that superior visual functioning may be due to years spent practicing through an optimized physical, technical and tactical training approach.[80]

8. Player Profiling and Training Implementation

8.1 Effective Physical Screening

In establishing the physical attributes of the golfer and their associated on-course physiological status, a periodized approach to physical assessment is required.[9] The process of physical screening should be the first strategy of players and coaches in developing an effective conditioning programme. Assembling a team to support the player will only be effective if a starting point for player development is established. As outlined by McMaster et al.[22] and Russell and Owies,[61] a range of assessment approaches should be applied to effectively evaluate the player's strengths and weaknesses, establish baseline measures and provide the educational impetus for player development autonomy. As indicated in table IV, a wide range of assessment methods have been used within the research to assess the physical attributes of golfers.

The application of self-assessment provides a starting point for the player, in which basic screening procedures and techniques can be integrated into the development plan. Allowing for regular self-monitoring ensures continuous reflection and refinements to the plan. With questionnaire-based resources[84] and comprehensive online facilities available to both player and coach (e.g. Titleist Performance Institute, http://www.mytpi.com), self-evaluation packages provide the tools that allow the player to feel in control of their own development. However, the need for more scientifically rigorous and reliable screening practices across a wider range of physiological indices will provide both player and coach with more specific diagnoses. These may include measures of anatomical characteristics and physical anomalies, dynamic strength and functional capabilities, movement ranges and possible impingements, cardiovascular capacity and readiness for exercise, specific nutritional practices and general dietary habits, podiatric and optometric functioning, and injury screening. With a full musculoskeletal examination,[72] aerobic fitness evaluation,[62] functional strength measurement,[85] nutritional and dietary record-taking[21] and medical assessment,[9] the physical screening process should be viewed by all coaches and players as a fundamental stage in optimizing their physical state.

Further, considering the biomechanics of the golf swing,[1] a player's physicality will have significant impact on their ability to physically function. Effective evaluation by a clinician to determine any anatomical or functional complications will also allow for correct interventions, such as custom-fitted orthotics, appropriate shoe type and regular shoe replacement, thereby reducing any compensatory mechanisms that could limit the achievement of movement potential.

8.2 Physical Training to Improve Golf Performance

Through functional training of joint range of motion, flexibility, functional strength and dynamic postural balance, and segmental stabilization, meaningful improvements in club swing range, speed and power have been observed. As is highlighted in table V, it is now clear that physical conditioning in the areas of golf-specific flexibility, strength and core stability at least 3 to 4 times per week over a period of 8 weeks will significantly improve club head velocity by an average of 4.2%

Table IV. Physical screening assessments used to identify physical attributes of the golfer

Physical attribute	Assessment method	References
Cardiorespiratory fitness		
$\dot{V}O_{2max}$	Incremental exercise assessment (bicycle/treadmill)	57,61,62
	2-Minute step test	81
	One-mile walking test	10,60
Lung function (FVC, FEV, PEF)	Spirometry	57
Resting heart rate	Seated rest	62
HR_{max}	Incremental exercise assessment (bicycle/treadmill)	57,62
Anaerobic functioning		
Peak power output	Wingate 30-second sprint test	58
Functional strength		
Isolated single/multi-joint strength	Isokinetic dynamometer	10,61
	Maximal repetition on static machines/free-weights	59,68
Grip strength	Handgrip dynamometer	57,60,62
Functional power		
Upper limb dynamic power	Medicine ball throw	68
Lower limb dynamic power	Vertical jump/standing board jump	60,62
Flexibility/range of motion		
Functional range of motion	Flexibility machine (i.e. torso rotator) Goniometry assessment	10,59-61,82
Global flexibility (lower back/hamstrings)	Sit-and-reach test	19,23,62
Balance		
Postural stability	Stork test (bilateral balance with open/closed eye)	10,60
Anthropometry		
Physical dimensions	Length, breadth and girth measures	59
Body fat	Skinfolds assessment (3/4/7-site)	57,59-61
Somatotype	Heath-Carter assessment instrument	83

FEV = forced expiratory volume; **FVC** = forced vital capacity; $\mathbf{HR_{max}}$ = maximal heart rate; **PEF** = peak expiratory flow; $\mathbf{\dot{V}O_{2max}}$ = maximal oxygen uptake.

and add up to 5.6% extra distance on a drive (14 yards extra of a 250 yard drive [13 m extra of 231 m drive]). With research focusing on functional development of the shoulder, torso and hip following foundation developments of whole-body strength, flexibility and postural stability,[68,87] recommendations focus on the need for golf-specific movement drills to replicate the swing as closely as possible.[67,68] With a well rounded, periodized resistance training programme that develops functional strength at speed (i.e. power), the golfer needs to develop golf-specific power during the dynamic movement of a swing.[85] This can be achieved by ensuring that any resistance and flexibility training targets the active muscle groups in a movement-specific way necessary to bring power transfer to the golf swing.

Despite the relatively low cardiorespiratory requirements of golf, any physical conditioning programme should contain aerobic-based activity to support the training and competition demands. Regular endurance-based exercise (i.e. 3 to 5 times per week for 20–60 minutes), functioning at an intensity equivalent to 60–80% of maximal heart rate, will provide the golfer with sufficient effective and safe cardiovascular conditioning.[90] For the aerobically unconditioned golfer, maintaining workloads over an undulating course for up to 6 hours in unfavourable conditions will induce cardiorespiratory, metabolic and hormonal stress leading to sensations of fatigue. By developing an effective training programme, foundation physical conditioning will support increases in resistance training, practice and competition.

Table V. Golf performance changes as an effect of physical conditioning training. All results are mean ± SD (where reported)

Study (year)	No. of subjects	Sex	Age (y)	Handicap	Training type	Duration (wk)	Frequency (d/wk)	Change in performance[a]
Lennon[19] (1999)	7	M	16	?	Strength/flexibility	8	4	>5 iron hitting distance
Hetu et al.[23] (1998)	17	M/F	52.4	?	Strength/flexibility	8	2	>6.2% club-head velocity
Thompson and Osness[25] (2004)	19	M	64.3	Mixed	Strength/flexibility	8	3	>2.7% club-head velocity
Jones[66] (1999)	16	M	51.9	?	PNF stretching	8	3	>7.2% club-head velocity
Doran et al.[68] (2006)	10	M	19.8	0	Strength/flexibility	11	3	>0.6% club-head velocity (NS)
	6	F	18.5	5–10	Strength/flexibility	11	3	>3.4% club-head velocity (NS)
Fletcher and Hartwell[86] (2004)	11	M	29	5.5 ± 3.3	Strength/plyometric	8	2	>1.5% club-head velocity >4.3% driving distance
Lephart et al.[87] (2007)	15	M	47.2	12.1 ± 6.4	Strength/flexibility	8	3–4	>5.2% club-head velocity >6.8% driving distance
Thompson et al.[81] (2007)	11	M	70.7	Mixed	Functional training[b]	8	3	>4.9% club-head velocity
Larkin et al.[88] (1990)	4	?	?	?	Strength/flexibility	3	?	>45% trunk rotational power
Wescott et al.[89] (1996)	17	M	57	?	Strength/flexibility	8	4	>6% club-head velocity

a All changes in performance are significant ($p < 0.05$) unless stated.

b Functional training = flexibility, core stability, balance and resistance exercises.

F = female; **M** = male; **NS** = nonsignificant ($p > 0.05$); **PNF** = proprioceptive neuromuscular facilitation; ? indicates not specified.

9. Long-Term Monitoring for Performance Success

A player development strategy necessary to achieve long-term performance success should include regular monitoring of physical development to determine adaptive response to training.[91] The implementation of player monitoring to track physical development,[57] evaluate the adaptive impact of physical training on performance,[68] and even predict golfing success,[92] can facilitate greater specificity of training approaches and effective long-term planning of physical conditioning programmes. Limited available evidence exist that documents the impact long-term monitoring has on developing golf performance success. Pheasey[57] is the only one to report provision of ongoing physiological support over an extended period (5 years). Assessing elite female golfers twice a year, once before the competitive season (March–April) and once after (October–November), findings reveal marked improvements across a range of physical attributes. For one player over a 3-year period, reductions in body mass (73.8–65.8 kg), reductions in body fat (30.1–23.9%), increases in $\dot{V}O_{2max}$ (29.2–45.7 mL/min/kg) and increases in maximal heart rate (183–198 beats/min) were recorded. By utilizing the bi-yearly assessment findings to implement individual training programmes to each player, the author noted that specificity ensured effectiveness (increased adherence) and compatibility with other support providers (i.e. physiotherapists). Although the impact such physiological adaptations had on golf success were not documented directly, accounts of competitive achievements throughout the 5-year monitoring period do underpin the importance of long-term physiological support to player development. Further research is warranted to elucidate the association between long-term monitoring, training implementation and golf performance success.

By establishing the relationship between physical attributes and golf performance, practitioners can implement more focused and effective development strategies that will have a direct impact on success. Attempting to identify physiological correlates of golf performance, Wells et al.[92] found the best predictors of success were core strength, stability, flexibility, balance and peripheral muscle strength. However, considering that golf success was broken down into average score, greens in regulation, short game measures and putting accuracy, such findings provide only tentative conclusions when attempting to establish which physical attributes best relate to golf achievement.

10. Physical Development Model for Golf

It is now well established that the optimization of golf performance is a multifactorial process[16,21] and that the available scientific literature supports the notion that physical training can increase aspects of golf performance.[10,25] For effective player development to occur, a strategy must be in place to ensure that evidence is constructively applied to develop corrective intervention measures. For the practitioner to plan effective long-term player optimization, such intervention strategies should positively assist the player to enhance their physiology. As represented in figure 3, a physical development framework for optimization in golf provides a systematic manner in which physical aspects of the player can be enhanced. In order to establish a physiological support system that truly pushes the limits of performance, a formal systematic process of data gathering, player screening, player profiling, training implementation and long-term development planning must occur. Through a process of implementation, evaluation and development, the following questions can assist when applying the model:

- Can our current level of understanding about physiological demands/requirements of golf at a micro/macro level be extended further?
- Are all the physical attributes that may contribute to golf performance success known?
- Are the current assessment methods being deployed suitable for golf?

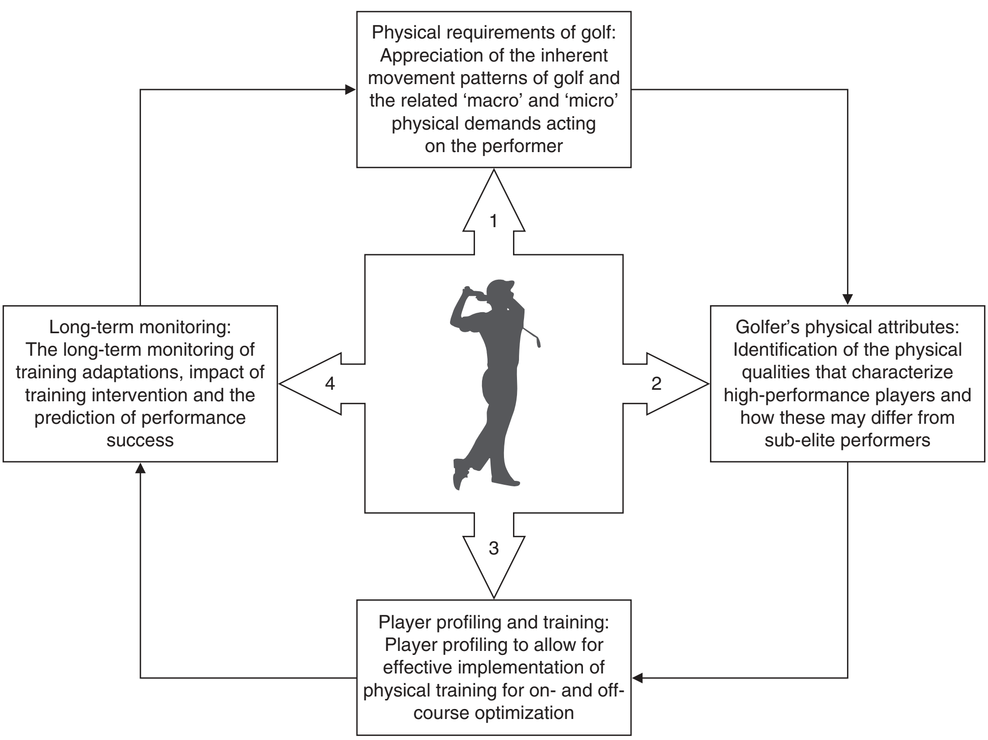

Fig. 3. A physical development framework for optimization in golf.

- Can specific training approaches be refined further to optimize adaptive responses specific to golf?
- What contribution does physical conditioning have on overall golf success, and can a predictive model be developed?

Without a systematic approach, the long-term physical development of the player will not lead to optimal performance on course, and will obstruct the ability to achieve peak physical state. It is through a continual cyclic process where each stage of the model informs the next that the attainment of consistent high performance can be realized.

11. Conclusions and Recommendations

A growing body of research evidence supports the role physiology plays in the achievement of overall golf performance success. An understanding of the dynamic muscle activation patterns during the swing, the physiological demands of on-course performance, the impact physical and anatomical characteristics have on movement, physical conditioning approaches and measurement and evaluation techniques for golf has moved the importance of physiology and physical conditioning programmes higher up the coach, player and sport scientist's agenda.

For effective long-term player development, implementation of an effective strategy will increase the potential for performance success. By appreciating the requirements of competitive golf performance, specific player attributes can be determined using appropriate and golf-specific assessment methods. Providing a player profile through comprehensive physical screening allows for specific conditioning programmes to be developed. Monitoring player development through continual assessment of training and associated adaptive responses provides an indication as to the key physical factors that may impact most on performance success. Through a cyclic process, the physical development model (figure 3) offers a framework by which a continual understanding of the physiology of golf can evolve. The attainment of consistent high performance requires effective physical conditioning that is carefully designed and monitored in accordance with the requirements of golf and the attributes of the player.

Further research needs to focus more specifically on physiological aspects relating to women, junior and disability groups. It should not be assumed that research findings, associated performance models and practical applications apply to all, and therefore caution must be taken when translating and applying research to specific performance groups.

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Correspondence: Dr *Mark F. Smith*, Department of Sport, Coaching and Exercise Science, University of Lincoln, Lincoln LN7 6TS, UK.
E-mail: mfsmith@lincoln.ac.uk

