Golf Science

Eric Wallace, Sport and Exercise Sciences Research Institute, University of Ulster, Newtownabbey, Co Antrim BT37 0QB.
Kieran Kingston, Cardiff School of Sport, University of Wales Institute Cardiff, Cardiff CF236XD.
Martin Strangwood, Sports Materials Research Group, Department of Metallurgy and Materials, University of Birmingham, Edgbaston Birmingham, B15 2TT.
Ian Kenny, Biomechanics Research Unit, Physical Education & Sport Sciences Department, University of Limerick, Ireland.

1.1 INTRODUCTION

This chapter aims to provide an overview of some of the key issues and developments in golf science over the last few years - essentially by reviewing some papers leading up to the last World Scientific Congress of Golf (2002) and others subsequent to the publication by Farrally et al (2003) on golf science at the beginning of the 21st century. As such, it is recognised that the material presented is by no means inclusive of all worthwhile golf research during this time period; rather it is intended to reflect on the main research domains in golf performance of the authors, namely biomechanics and performance measures, psychology, and technology. Cochran (2002) stated that whilst the benefit of high-tech equipment based on genuine science is real, it is nonetheless small. Anecdotally, golfers often report greater performance benefits than testing and theory suggest, supporting the self-efficacy brought to the game by technologically advanced equipment. Furthermore, enhanced teaching, improved fitness and course maintenance have all contributed to improved performances in the game.

1.2 GOLF BIOMECHANICS AND PERFORMANCE MEASURES

Farrally et al (2003) indicated that the four world congresses to date had attracted considerable biomechanical research (with 29 studies reported in total in the Proceedings of the WSCG), yet they claimed that understanding of the golfer’s interaction with the club was still too crude to fit clubs properly and we were still a long way from understanding the complex movement pattern of the golf swing. The biomechanics of the golf swing has remained a popular area of study, with a number of research publications appearing in a range of journals and refereed conference proceedings. A comprehensive review article on the role of biomechanics in maximising distance and accuracy of golf shots has since been published (Hume et al. 2005) Experimental work involving single-subject and group designs has also been published, as well as mathematical and computer modelling studies. There has been considerable interest in the traditional areas of kinematics and kinetics of the golf swing, for a range of players of varying ability, but with little consideration of
the female golfer. The mechanisms by which players generate high club head velocity have also been further investigated, along with a number of studies on putting techniques and putting devices. The utilisation of high specification launch monitors has permitted investigations into player/equipment interactions and performance measures, while biomechanical analysis methods of the swing and the nature of swing planes have also received attention. Biomechanical analysis of the golf swing has sought to characterise swing patterns for elite and non-elite golfers, and more recently, describe the interaction between the golfer and club.

The descriptive kinematic analysis of shoulder motion during the swing by Mitchell et al. (2003) provided a baseline reference on the range of motion of the shoulders for college, middle-aged and senior golfers. Senior golfers were observed to demonstrate 38° less rotation and 18° more right arm abduction at the top of the backswing compared to college golfers. Wallace et al. (2004) examined the effects of long drivers on selected body kinematics and temporal aspects of the golf swing, and found no driver length effects on transverse hip rotation at key positions during the swing, but significant effects on shoulder rotation at impact. Longer club length resulted in an increase in overall swing duration, yet the temporal phasing of the backswing and downswing components was unaffected. In one of the few studies to include an examination of female golf swings, Egret et al. (2006) observed females had wide swings with larger hip and shoulder rotations at the top of the backswing compared to men, and concluded that two kinematic patterns existed yet there were no significant differences in club head speed between the male and female golfers. An important methodological paper by Wheat et al. (2007) showed that thorax alignment using Cardan angles would not be affected by out-of-plane motion, whereas transverse plane alignment of the upper body calculated using the inter-acromion vector (commonly used in many previous studies) while valid at the address position was not an accurate measure at the top of the backswing or at impact.

In relation to swing planes, Coleman and Rankin (2005) utilised 3-D kinematics to demonstrate, contrary to many previous models and coaching theories, that the left arm and shoulder girdle do not move in a consistent plane throughout the downswing, thereby calling for more complex and realistic models for future simulations. In a subsequent study, Coleman and Anderson (2007) concluded that it was mathematically possible to fit a single plane to the 3-D downswing motion of the golf club for experienced golfers, but the fit varied between golfers and also between clubs (driver, 5-iron and pitching wedge).

The means by which high club head speed is generated has remained topical. The kinematic chain involving hip and thoracic rotations followed by sequential actions of the arms, forearms and wrists has been studied. In an experimental study, Teu et al. (2006) provide a novel method of velocity analysis using dual Euler angles, which they showed provides an option in assessing the contributions of individual segment rotations in the production of the relevant velocity of the end-effector. Sprigings and Mackenzie (2002) carried out a simulation study to examine the effects of a delayed wrist release technique (uncocking) and to identify the sources of power that account for increasing club head speed. These authors showed a small advantage in employing this delayed release at the wrist, but the magnitude of the gains were significantly less than previously reported. Their simulations also provided muscle power magnitude values for the shoulders, wrist and torso that contributed to the swing.
Combined with biomechanical analysis, research using launch monitors has permitted investigations into the mechanisms by which club head velocity is generated, and the subsequent ball launch characteristics. Fradkin et al. (2004) found a strong linear relationship between golfers’ mean club head velocity at impact and handicap. As handicap increased, club head velocity at impact decreased. An equation was derived (Equation 1.1) whereby, using the 45 golfers studied, club head velocity could be derived from handicap, thus:

\[
\text{Mean club head velocity} = e^{4.065 - 0.0214 \times \text{handicap}}
\] (1.1)

Previously, Wallace and Hubbell (2001) studied 84 golfers with a wide range of handicaps to determine relationships between club head speed for 5-irons and various anthropometric measures, physical fitness factors and handicap. The regression equation for statistically significant partial correlations with club head speed is given in (Equation 1.2).

\[
\text{CLUBHEAD SPEED} = [90.05 (+/- 16.06)] - [0.898 (+/- 0.29) \text{HANICAP}] + [0.109 (+/- 0.07) \text{BACK STRENGTH}] + [11.82 (+/- 7.75) \text{LEG POWER}].
\] (1.2)

Wallace et al. (2007) described the ball launch characteristics of ball velocity, spin and launch angle for skilled golfers using long drivers using a stereoscopic high speed launch monitor. They concluded that all drivers demonstrated similar ball launch characteristics, but the longest driver of 52” yielded small, but significant, gains in ball velocity compared to the other drivers studied. Similarly, Kenny (2006) reported increased club head velocity when elite golfers used a driver of 50”, some 2” longer than the current length limits. Recently, the role of the upper torso and pelvis rotation in producing high ball velocity has been re-visited with 3-D kinematics combined with launch monitor data (Myers et al., 2008). These authors refer to the ‘X-factor’ term commonly used by teaching professionals and reported in many scientific studies, or ‘segment separation’ as the difference in axial rotation between the upper torso and the pelvis at the top of the backswing. However, while using the global x-axis, as opposed to employing Cardan angles as outlined by Wheat et al. (2007), Myers et al. (2008) showed torso-pelvis separation during the swing contributes to greater upper torso rotation velocity and torso-pelvis separation velocities during the downswing, thereby resulting in greater ball velocity. McCloy et al. (2006) also characterised ball launch conditions and club head velocity for a range of irons and elite level golfers. They found that as loft increased, club head velocity decreased, as would be expected, but also that club head angle of attack, or dynamic loft, increased. These findings contribute towards a baseline reference for future studies that may seek to determine specific iron club features, such as shaft dynamic stiffness effects. Research relating to driver shot performance appears to have concentrated on club head velocity and ball velocities as they relate to distance. Few studies have investigated accuracy, except for example those by Werner and Greig (2000) and Kenny (2006). Another issue relates to ecological validity (Wheat et al., 2007) due to the bulk of biomechanical analyses being conducted in the laboratory.

Ball and Best (2006) in their examination of weight transfer patterns using cluster analysis identified two major centre of pressure (COP) patterns during the downswing that were evident in both professional, highly skilled golfers as well as
high handicap players, thus indicating neither style was a technical error. Later, Ball and Best (2007) demonstrated specific and unique positioning and range of COP for each style, leading them to the conclusion of the importance of identifying different movement strategies before evaluating performance measures. Biomechanics researchers such as Hatze (2005), and noted by Farrally et al. (2003) have indeed discussed the need for subject-specific investigation into human motion by means of computer models and movement simulation. Development of models that are anthropometrically tailored for individual subjects are called for, thereby providing a better correlation between experimental and theoretical results. Kenny et al. (2006) developed a large-scale full-body musculoskeletal model to investigate the kinematics and kinetics of the golf swing for an elite golfer. The model was driven using three dimensional movement data from one subject (a plus-1 handicap golfer). Computer simulations replicated the swing of the golfer with a correlation of 0.999 between experimental kinematic data and simulated kinematics. Figure 1.2.1 shows an image of a simulated swing using a driving club. Such a model could be used to further investigate the hip and shoulder kinematics, characterisation of swing planes and timing, as well as club-hand kinetics and muscle forces generated.

Figure 1.2.1 Musculoskeletal golfer model

Similar models have been developed using biomechanical modelling software by Nesbit (2005) and Nesbit & Ribadeneira (2003) investigating the work and power outputs by the golfer during a golf swing. They found that joint torque was markedly different between subjects, but concluded that factoring in different swing speeds, the energy losses at impact, and club aerodynamic drag resulted in a reliable simulation of the kinetics of the golf swing.

1.3 GOLF PSYCHOLOGY

Since Farrally et al.’s (2003) review of golf science at the start of the 20th Century, research into the psychology of golf has continued to flourish. In the context of this chapter, golf psychology research encompasses studies that use golfers as the participant population, as well those explicitly utilising golf tasks to examine a
specific psychological aspect of sport. This is not to say that there are not numerous studies across the gamut of theoretical areas comprising sport psychology, the findings of which would readily transfer to golfers and golf type sports. The research has taken (and appeared in) a number of forms, however, for the purpose of this overview, we are only going to describe research findings communicated through peer-reviewed academic research journals. Broadly speaking, the three areas of sport psychology that have received concerted attention with respect to golf are: stress and coping; the use of imagery; and focus of attention. We are not in any way suggesting that there has not been other golf related research in sport psychology since 2003; indeed, within conference presentations and on-line sport science resources, work has been presented in the areas of motivation, the yips and choking, and the caddie/golfer relationship, for example.

Players and coaches continue to recognise the importance of psychological skills in golf, particularly at the highest level (Thomas, 2001). Indeed, it is a relatively recent phenomenon to observe at least four or five practising sport psychologists supporting clients at a typical European Tour golf event. This ‘coming out’ of the discipline at an applied level makes it incumbent upon the academic community to ensure that applied sport psychology is supported by good science practised within meaningful, well conceived, ecologically valid research studies. Farrally et al. (2003) in their review acknowledged that there had been significant research in the areas of: stress and anxiety; performance routines; process goals; mood state; personality; attention; and imagery. It would be reasonable to suggest that in a few areas this work has moved forward, however, in others the status quo has remained. As mentioned previously, our search of the peer-reviewed journal literature illustrates significant developments in the areas of: imagery; stress (specifically sources and coping strategies); and focus of attention – it is this work, we will now briefly review.

Imagery, as well as being identified as a pivotal psychological skill for golfers, has in recent years become very popular amongst sport psychology researchers. The efficacy of a structured imagery training programme has been consistently supported (Munroe et al. 2000). Building upon this momentum, Smith and Holmes (2004) sought to identify the most effective imagery modality for enhancing putting performance using a sample of 40 male golfers (mean handicap = 3.54). Their results indicated that in comparison to self teaching (through reading) and following a script, video (self-modelling) and audio modes were more effective in improving performance. They concluded that imagery training should allow the participant to experience the motor representation of the skill as fully as possible. This supports the proposal that imagery of movement exercises and encodes the relevant brain areas which in turn facilitates performance (cf. Smith and Holmes, 2004). Gregg and Hall (2006) examined the magnitude of, and the influence of age and skill level on imagery use. Supporting the contentions of Cumming and Hall (2002), with regards to the relationship between imagery use and deliberate practice, Gregg and Hall found that as handicap level increased (i.e. players were less skilled), imagery use decreased. They also reported that imagery use decreased with advancing years, suggesting that imagery training should be an integral part of physical skill development in golf. Finally, they noted that, factors such as setting (i.e. practice versus competition), time of season, and confidence levels also impact on imagery use.
Previous research has illustrated the potentially debilitating effects of psychological stress on golf performance (e.g. Hardy and Mullen, 2001; Masters, 1992). Clarifying this relationship, Hassmen et al. (2004) suggested that variability in athlete perceptions of their physiological arousal (somatic anxiety) was significantly related to variability in actual performance, suggesting that self-regulation and coping strategies are critical for effective performance. Associated with this proposal, there is an increasing body of research literature concerned with sources of such stress, and more specifically the strategies for coping with stressors in golf. Nicholls et al. (2005), examined the coping strategies of eighteen international age-group golfers, and found that effective cognitive coping strategies were employed. These included, for example; rationalising mistakes, thought blocking, reappraising, positive self-talk, and adhering to their routine. These paralleled many of the findings of Giacobbi et al. (2004) who, in examining the coping responses of skilled and moderately skilled golfers, found that golfers used more than one coping strategy; further, their strategies included such things as maintaining a positive perspective in the face of adversity, interpreting information positively, and/or retaining a positive focus. Again, in terms of frequency, Nicholls et al. (2005) found that, although a wide range of specific stressors have been identified in the literature, for any given athlete, there were actually a relatively small number of acknowledged stressors, but these were experienced repeatedly. Furthermore, as the season progressed, golfers reported that mental errors occurred more frequently than physical errors, illustrating the value of ongoing sport psychology support for athletes throughout the season.

In the past ten years there has been a thrust in attempts to identify and clarify the most appropriate focus for a performer’s attention while executing skills. Based on the work of Wulf and associates (e.g. Wulf et al. 1999; Wulf and Prinz, 2001), it has been argued that a focus on bodily movements (an internal focus of attention) is less effective than paying attention to the anticipated environmental effects of one’s movements (an external focus of attention), for example, the proposed target. More specifically, Perkins-Ceccatto et al. (2003) using a golf pitching task, found that highly-skilled golfers performed better with an external focus of attention, yet low-skilled golfers performed better when focusing on the form of their swing and the force required to hit the ball a set distance. They concluded that, once the fundamentals of the skill have been learned, performers will benefit most from concentrating on the effects of their movement, rather than by attending to the action of the golf stroke. Conversely, before the fundamentals are grasped, it is better to concentrate on the movements required to achieve this objective. Clearly this has important implications for coaching golf.

In addition to carrying out research using refined and more ecologically valid methodologies to build on previous work, preliminary theory-building work in other areas of sport psychology has opened the door for future research in golf. This research has the potential to prove fruitful in further informing applied practitioners. The efficacy of pre-performance routines is not in any doubt (see, Jackson, 2001) however, understanding the mechanisms behind their positive effects may enable them to be taught more efficiently. Further, there have been a number of major theoretical developments in areas such as: sources of confidence, motivational profiling, and mental toughness. These advances will enable those with a specific interest in golf science to engage in research that is both well-grounded conceptually,
and also has the potential to inform teaching, coaching, and skill development within the sport.

1.4 GOLF TECHNOLOGY

The development of golf equipment has been a feature of the history of golf and continues apace. Whilst much historical development has been empirical, recently there has been much more systematic study into equipment and its operation aided by increased development of high-speed imaging and measurement equipment. These techniques have allowed a more quantitative determination of the dynamic performance of equipment and of materials properties. Knowledge of more appropriate properties means that models, such as finite element, are more accurate and can be used in a more predictive capacity in optimising equipment design and tailoring it to specific golfers.

Throughout most of the 1990s, one of the major issues in equipment technology was that of high coefficient of restitution (CoR) drivers, which, coupled with the introduction of Titleist ProV1 and ProV1x solid golf balls, resulted in a steady increase in drive distances. As Fig. 1.3.1 shows the major increases in drive distances occurred between 1993 and 2000 as titanium-based alloys were used in hollow, oversized drivers. During this period the use of forged metastable β-Ti alloys with higher strength / modulus ratios than the cast α + β titanium-based alloys originally used, coupled with control of the size and position of joints between face, crown and sole resulted in drivers approaching the USGA / R&A CoR limit. Thus, the rate of drive distance increase has slowed considerably over the period 2003 – 2007, Fig. 1.4.1.

![Average US PGA Tour Drive Distances](image-url)
Figure 1.4.1. Variation in average US PGA drive distances with year (each point represents around 32,000 measurements). The increases prior to 1993 are largely associated with golfer conditioning and training, whilst the sudden increases in 2001 and 2003 are associated with ball variations. [Graph constructed from data on US PGA website - accessed 5/06/07]

Drive distances are largely associated with ball speed off the driver face, which is achieved by reducing head stiffness so that viscoelastic ball deformation, which loses energy during impact, is replaced by linear elastic head deformation (with negligible energy loss). As fully metallic alloy heads are reaching the conformance limit, then the focus of research has moved away from outright distance to increased control and modified launch conditions. This increased ‘forgiveness’ of drivers is achieved through both mechanical design and material usage. The change in materials is often achieved through combination of a titanium-based alloy face and sole with a carbon fibre composite crown. The introduction of a polymer matrix composite increases the viscoelastic nature of deformation during impact of the head which will increase the energy loss during impact and so will compromise absolute CoR. However, the substitution of lower density composite material (1.7 g cm\(^{-3}\)) for \(\beta\)-Ti (4.7 g cm\(^{-3}\)) results in the ability to re-distribute mass lower in the head to modify launch conditions, particularly increasing launch angle. In mixed material heads the face and sole are constructed from Ti-based alloys due to the poor wear resistance of epoxy resin matrix systems. Whilst allowing mass redistribution the incorporation of polymer matrix composites introduces potentially greater material variability, as has been noted in carbon fibre composite shafts (Huntley et al., 2006), Fig. 1.4.2, as well as a greater rate-dependence to the head properties.
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Figure 1.4.2. (a) Variation in fundamental bending frequency around the circumference of a carbon fibre composite shaft associated with variations in fibre volume fractions through the cross-section of the shaft (b); the fibres appear as light dots.

The strain rate-dependence of composite material properties has traditionally been limited to static and crash situations, i.e. mainly at very low and very high speeds, which are not appropriate to sporting situations such as golf, tennis and skiing. Investigations into dynamic properties over more representative deformation rates have identified relationships between material properties and performance for shafts and balls (Strangwood et al., 2006) leading to more accurate and predictive models (Rowe, 2007). Extension of these studies to composites in drivers along with improved homogeneity in properties may lead to incremental improvements in the performance of drivers, but are unlikely to give effects as large as those seen in the 1990s. The majority of work in this area has been carried out by major manufacturers, leading to clubs such as the Mizuno MX-500 (Mizunousa, 2007), but with few open reports apart from patents.

The use of lower density materials with higher strength allows downgauging of sections increasing the amount of mass available for redistribution as well as facilitating less traditional head shapes. This has allowed ‘squarer’ heads, such as the FT-i (Callaway, 2007) and Sasquatch (Nike, 2007) with larger moment of inertia (MoI) values to be developed. Higher MoI values reduce the rotation of the head during the downswing and impact and so reduce the variability in impact conditions for a range of swings. As such, they offer little in terms of performance increase for golfers with consistent swings, but are more forgiving of golfers with less consistent swings. This effect will also have its limit (USGA and R&A conformance limits), but there will be incremental improvements as the materials (e.g. higher strength nanocomposites), their homogeneity and their dynamic properties are optimised to high MoI designs.

Whilst the head is important, much work is continuing into increased understanding of the behaviour of golf shafts during the golf swing, particularly with a view to optimising shaft performance to individual golfer’s swings. This is concentrating on carbon fibre composite shafts due to the design flexibility provided
by sheet laminate lay-up (Lee and Kim, 2006; Kim et al., 2006). These studies will need to address the inhomogeneity and dynamic issues mentioned above, but indicate greater interest in the dynamic interaction of the golfer and their equipment. This will assume more importance in future research with enhanced interdisciplinarity between materials, mechanical engineering, biomechanics and psychology.

Finally, the use of high-speed imaging has allowed the interaction of golf balls with normal and inclined plates (grooved and un-grooved) to be quantified and related to material properties and ball construction. This has been accomplished for both normal impact, i.e. distance (Johnson, 2005; Strangwood et al., 2006), and oblique impact, i.e. spin generation (Monk et al., 2005; Cornish et al., 2006). These studies have identified material property ranges necessary for spin generation – interaction of a soft cover with grooves on the face, with a soft core to give a large contact area on impact, but separated by a hard mantle to reduce viscoelastic losses and maintain speed off the face. These trends and the greater understanding of the effects of graded material properties are borne out by the performance of recent three- and four-piece balls. Coupled with better models of ball behaviour (Rowe, 2007; Tanaka et al., 2006) and more appropriate data (Mase and Kersten, 2004) the design of balls appropriate to particular swing speeds is possible.

1.5 CONCLUSION

Golf remains a popular and topical sport for research. Since 2003, biomechanical studies have continued to examine the kinematics of the swing with some additional knowledge gained in terms of kinematic chain motion. A rationalised coordinate system for studying hip and torso rotations during the swing has been suggested, that may provide a further understanding in the future of the generation of end-effector velocity. The need for consideration of human variability in the golf swing has been reinforced, with some advancement made in terms of representative simulation models. Future work should aim to validate laboratory-based tests so that further ‘ecologically’ sound experimental investigations can be conducted, which in turn could be used with simulation models that have the sophistication to produce realistic results, yet without unnecessary compromising complexities. In psychology, post Farrally et al.’s (2003) review, a number of significant developments have been identified in, for example, the fields of: imagery, sources of stress and coping, and identifying an optimal focus of attention. The major implications of this work suggest that: a) imagery training should be an integral part of golf skill development, and the nature of this training should be tailored according to the context, and the confidence and the skill level of the performer; b) in absolute terms, individual golfers experience a small number of stressors, but these stressors often reoccur throughout their round – they also use a variety of strategies even to cope with the same stressor; c) once the fundamentals of the golf swing are mastered, learners will benefit most from focusing their attention on the effects of their swing, rather than attending to the action itself. Future work, as well as building on current knowledge bases, should consider theoretical developments in, for example areas of confidence, motivation and mental toughness. The large market for golf equipment and for technology to aid golfers means that this will continue to be a fertile ground for innovation. Recent studies have shown a more systematic approach to enhance
understanding of the dynamic phenomena involved. This has allowed real effects to be determined and optimised through materials, design and construction. Future trends appear to be towards greater understanding of the interaction of the golfer with their equipment so that tailoring of equipment for a wider range of abilities rather than just the elite will become possible.

1.6 REFERENCES


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