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The Role of Biomechanics in Maximising Distance and Accuracy of Golf Shots

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Abstract

Golf biomechanics applies the principles and technique of mechanics to the structure and function of the golfer in an effort to improve golf technique and performance. A common recommendation for technical correction is maintaining a single fixed centre hub of rotation with a two-lever one-hinge moment arm to impart force on the ball. The primary and secondary spinal angles are important for conservation of angular momentum using the kinetic link principle to generate high club-head velocity. When the golfer wants to maximise the distance of their drives, relatively large ground reaction forces (GRF) need to be produced. However, during the backswing, a greater proportion of the GRF will be observed on the back foot, with transfer of the GRF on to the front foot during the downswing/acceleration phase. Rapidly stretching hip, trunk and upper limb muscles during the backswing, maximising the X-factor early in the downswing, and uncocking the wrists when the lead arm is about 30° below the horizontal will take advantage of the summation of force principle. This will help generate large angular velocity of the club head, and ultimately ball displacement. Physical conditioning will help to recruit the muscles in the correct sequence and to optimum effect. To maximise the accuracy of chipping and putting shots, the golfer should produce a lower grip on the club and a slower/shorter backswing. Consistent patterns of shoulder and wrist movements and temporal patterning result in successful chip shots. Qualitative and quantitative methods are used to biomechanically assess golf techniques. Two- and three-dimensional videography, force plate analysis and electromyography techniques have been employed. The common golf biomechanics principles necessary to understand golf technique are stability, Newton's laws of motion (inertia, acceleration, action reaction), lever arms, conservation of angular momentum, projectiles, the kinetic link principle and the stretch-shorten cycle. Biomechanics has a role in maximising the distance and accuracy of all golf shots (swing and putting) by providing both qualitative and quantitative evidence of body angles, joint forces and muscle activity patterns. The quantitative biomechanical data needs to be interpreted by the biomechanist and translated into coaching points for golf professionals and coaches. An understanding of correct technique will help the sports medicine practitioner provide sound technical advice and should help reduce the risk of golfing injury.

Golf has become an increasingly popular sport, attracting new players of almost all ages and socioeconomic groups. Golf is practiced by 10–20% of the adult population in many countries[1] with an estimated 35 million participants worldwide (26.5 million golfers are in the US).[2] Technique can have a large effect on golf performance where the aim of the game is to hit the golf ball into a small hole in as few shots as possible.[3] In order to achieve this aim, the golfer must hit a variety of shots using the two principal movements in golf: swing and putting. The swing is realised with wood and iron clubs and putting uses a putter. The sand-wedge (iron number 10) and the pitching-wedge (iron number 11) are specially used to perform high trajectories. Each of these shots can be seen along a continuum of golf swings, with the drive and long irons utilising the greatest range of motion and largest forces, and the putt utilising the least range of motion and least force.

This review examines the role of biomechanics in maximising distance and accuracy of golf shots. The following questions are addressed:

- What is golf biomechanics?
- What is the role of biomechanics in maximising the distance and accuracy of swing and putt shots?
- What are common recommendations for technical and physical corrections in golf?
- What methods are used to biomechanically assess golf techniques?
- What are common golf biomechanics principles?

Four review articles,[1,4-6] 43 original research articles, 27 proceedings from the World Scientific Congress of Golf, ten conference abstracts, five books, three technical manuals, two web articles and six magazine articles (e.g. Golf Magazine) were reviewed. These were based on articles located by searching SportsDiscus, Medline, Current Contents, Cinahl, ABI/INFORM Global and ProQuest Direct databases and the internet (Journal of Biomechanics Online) using the key words ‘golf’, ‘biomechanics’ and ‘injury’. Manual searches were performed by looking through article reference lists.

1. Knowledge in Golf Biomechanics

A recent review by Farrally et al.,[6] summarised research findings in golf and identified the application of sound biomechanics to improve golf performance as important. Biomechanics is a scientific discipline that applies mechanical principles to understanding movement. Golf biomechanics applies the principles and technique of mechanics to the structure and function of the golfer in an effort to improve golf technique and performance. Therefore, a biomechanical assessment of the golf swing may include analysis of movement and muscle activation patterns as well as internal and external forces.

Biomechanics has been used in an attempt to characterise the ‘ideal’ golf swing, with the aim of improving performance and reducing the risk and severity of golf-related injuries.[7] According to Dillman and Lange[7] biomechanical studies have assessed the kinematic, kinetic and electromyographic characteristics of the golf swing. By using qualitative and quantitative biomechanical analyses tools, biomechanists have been able to describe the movement patterns of golfer’s swings as well as the resultant joint torques and patterns of muscle activity that produce these movements. Biomechanical research has focused on golf swings with limited biomechanical research conducted on putting. The difference in emphasis is due in part to the swing movement being performed with 17 clubs (six woods and 11 irons) compared with the putting just realised with the putter club. Therefore, this review provides more evidence for the role of biomechanics in maximising the distance and accuracy of swing shots than that of putting.

The following section on the role of biomechanics in maximising the distance and accuracy of golf swings and putting describes the kinematics and kinetics of swing and putting shots, and the effects of the stretch-shorten cycle (SSC) and physical conditioning on golf performance. A right-handed golfer is used for all descriptive purposes. The final section on the approach and methods a biomechanist takes to analysing golf, and some basic golf biomechanics terminology and principles, is provided to allow a more in-depth understanding of the theory of biomechanics and the application to golf.

2. The Role of Biomechanics in Maximising the Distance and Accuracy of Golf Swings and Putting

The primary goal of using the driver (wood and long irons) is to hit the ball as far as possible while still ensuring that the ball lands on the fairway. Consequently, a number of biomechanical principles may be able to be applied to the golf swing in order to maximise the length of these golf shots.

The displacement of a golf shot is a direct function of the club-head’s linear velocity at the point of impact between the club and the ball. The linear club-head velocity is then a function of the angular velocity of the club head and the length of the arm-club lever at the point of impact. Thus, to maximise ball displacement, the golfer must maximise the angular velocity of the club head and the length of the arm-club system at impact. While the length of the arm-club system is maximised by holding the club at the superior portion of the handle and having the elbows extended at the point of contact, the length of the arms and clubs have relatively finite limits. Consequently, most of the biomechanical research into maximising the distance of the driver and long irons has investigated the factors related to the angular velocity of the club head. These factors include the role of ground reaction forces (GRF) and transfer of bodyweight, use of the sequential summation of forces principle and utilisation of the SSC.

2.1 Kinematics and Kinetics of Swing Shots

The biomechanics of the golf swing has been reported by several authors.[8-17] Neal et al.[9,11,18,19] reported optimal golf swing kinetics and kinematics using 3-dimensional (3D) analysis techniques. Budney and Bellow[20] reported swing mechanics of a matched set of golf clubs and kinetic analysis of a golf swing.[21] Egret et al.[22] has reported analysis of 3D kinematics for three different clubs in golf swing. Video analysis systems such as SwingEye™,[23] **1** Sports Coach Digital Video System™[24] and AUT Golf Goggles Training System™[25] are being used to provide feedback for golfers to improve their swing technique.

Little research on chipping has been conducted from a biomechanical perspective. Abernethy et al.[26] compared the upper-limb muscle activity and kinematics, respectively, of expert and novice golfers performing shots with their pitching wedge, 9-iron and 7-iron to targets located 20m, 40m and 60m away. Abernethy et al.[26] reported that although considerable inter-subject variability in the muscle activity patterns was observed for the expert and novice group, the intra-subject variability of muscle activity for the expert players was quite low. This contrasted with the novice players where high levels of intra-subject variability in muscle activity were observed. Perhaps as a consequence of their lower variability in muscle activity, expert golfers had a significantly more consistent pattern of shoulder and wrist movements and temporal patterning of their chip shots than the novice players. The significantly greater variability in joint kinematics and muscle activity between trials for novice than expert golfers appeared to contribute significantly to the novice golfer's reduced chipping accuracy and inability to specify the required force.[26]

While a number of classification schemes have been used to describe the phases of the golf swing, this article divides the golf swing into the set-up (or address), backswing, downswing and follow-through phases. The set-up involves establishing the grip on the club (Vardon overlap grip, or interlock or baseball grips) and positioning the body with respect to the ball. The backswing consists of the preparatory movements that result in the club head rotating away from the ball. The downswing phase begins at the top of the backswing and concludes when the club makes contact with the ball. The follow-through occurs after ball contact.

2.1.1 Set-Up

According to Geisler[2] the set-up or starting position for executing a golf swing should align the golfer properly with the target, establish dynamic and static balance, be in a sound biomechanical position (i.e. golf posture) and provide an effective grip of the club. An effective grip allows the golfer to control the club-face and allows the club to hinge and unhinge during the golf swing. Grips can be termed strong, weak or neutral. For a right-hand player looking down at their grip, a strong grip is one in which the hands are rotated clockwise showing much of the dorsal aspect of the left hand. A weak grip is one in which the hands are rotated counter clockwise so the dorsal aspect of the right hand can be seen, while a neutral grip is one in which the hands are midway between the strong and weak positions. A strong grip increases the ability of the player to release the hands during the downswing and impact phases producing more speed but also more risk of miss-hits and off-line shots. Weak grips decrease the amount of hand speed contributed to the swing but allow more club-face control.[2] Geisler[2] indicated that golfers with $<10°$ radial deviation are more suited to a strong left-hand grip, whereas those with more normal radial deviation around 20° would be more comfortable with a neutral left-hand grip.

During the set-up, 50–60% of the golfer's weight should be on the back foot.[27] The knees should be flexed to 20–25°, the trunk flexed to approximately 45° at the hips (primary spinal angle), with a right lateral shoulder tilt of approximately 16° resulting from a combination of right lateral bending in the spine and slight depression and downward rotation of the right arm and scapula (secondary spinal angle) due to the right hand being placed lower on the club than the left hand.[2] Such a position is thought to be optimal for generating power and maintaining control of the golf swing.

1 The use of trade names is for product identification purposes only and does not imply endorsement.

2.1.2 Backswing

The purpose of the backswing is to position and align the golfer's hub centre and club head so that the golfer can execute an accurate and powerful downswing, to provide a base link for the downswing's kinetic chain, and to stretch the muscles and joint structures that are responsible for generating power in the downswing. The average duration of the backswing for elite players performing the drive has been found to be <1 second (0.82 seconds).[28] The backswing starts with a 'one-piece takeaway', where the triangle formed by the two arms and the chest should be maintained throughout the first 40–60cm, while the club head travels back along an imaginary line from the ball perpendicular to the line of the golfer's toes.[28,29] The shoulders then continue to rotate and pull the hips into a rotated position whilst the arms move upwards.[30] When the hands reach the level of the hips the right arms abducts, outwardly rotates and the right elbow flexes. The left arm adducts and inwardly rotates. These movements should keep the shaft of the club travelling along a plane (the swing plane). There is controversy as to where the plane should be, with some professionals teaching a two-plane method.[29] Each golfer's swing plane zone is determined by the set-up position of the club and the golfer, which will vary depending on differences in club length, lie angle (angle created between the club head and the shaft) and the set-up posture.[28]

There is also controversy surrounding the weight-shift principle.[31-34] Most players backswing motion results from shoulder and pelvis rotation around a fixed base of support rather than a lateral weight shift, which is thought to develop club-head speed from the large muscles in the buttocks, hips and legs. A large weight-shift or weight-transfer can move the golfer's centre of mass outside the base of support making the swing hard to control. The hips and torso produce approximately 10% of the total linear velocity in the downswing in skilled golfers, therefore, the lateral weight-shift technique does not help provide much club-head speed.[35] However, the speed of the swing has benefited by the centre of mass shifting exclusively in the intended direction of ball flight during impact in a study of hip and shoulder rotations during the golf swing of sub-10 handicap players.[31] Further investigations are required to determine the segmental contributions to different types of golf shot.

The average shoulder rotation (78–102°) and hip rotation (47–55°) at the top of the backswing vary depending on the level of the player.[2,12,31,36,37] The primary and secondary spine angles and the knee flexion angle should also be considered when assessing these rotation angles as shoulder and hip rotation can be affected by spine and knee angles. At the top of the backswing, the right arm is abducted to approximately 75–90° and externally rotated approximately 90°. The left elbow is extended, the left shoulder is inwardly rotated and horizontally adducted across the chest, the left scapula is abducted, elevated and outwardly rotated, and the wrist and hands are cocked (the angle between the club and forearm approaches a perpendicular position). This position results in the left posterior rotator cuff and scapular muscles being stretched, and the glenohumeral joint being in an impingement position. Golfers with radial deviation of 20° can achieve a wrist-cock position with minimal wrist extension, whilst golfers with limited radial deviation will use more wrist extension to gain the square hand and club face position at the top of the backswing. The range of motion in the left shoulder and spine will determine the length of the backswing. At the end of the backswing, the left leg (lead leg) bears approximately 40% of the bodyweight and is passively externally rotated because of the right pelvic rotation.[27] Some left tibial internal rotation and foot pronation will occur. If a golfer has limited hip external rotation or tibia internal rotation then the heel leaves the ground indicating stress on the left leg. The right pelvic rotation causes internal rotation of the right femur. If there is inadequate internal rotation of the right femur (i.e. <30°) the anterior superior iliac spines will tilt from the desired horizontal position (the right anterior superior iliac spine will raise up and move laterally back) and the right knee flexion angle will extend from the desired 20° knee flexion (i.e. the primary and secondary angles are changed). If there is limited hip internal rotation then the feet can be abducted 10–20° to help hip movement. Grip forces have been measured using force transducers on the handle of the club during the backswing.[38] Throughout the backswing, the left hand was firmly in control of the club while the right hand was passive.

2.1.3 Downswing

The purpose of the downswing is to return the club head to the ball in the correct plane with maximum velocity. An average duration for the downswing is 0.23 seconds[28] for elite golfers performing a drive. The downswing can be further divided into two subphases: (i) the forward swing phase, which initiates the downward motion of the club; and (ii) the acceleration phase, which accelerates the club downward.[39] A model swing has been described as having a single fixed centre hub of rotation with a two-lever, one-hinge moment arm to impart force on the ball.[28] The hub centre lies near the player's sternum. The hub acts as the centre around which the moment arm rotates on a specific plane (a biomechanical wheel and axle system). To produce an efficient shot, the player should keep the hub within the base of support.[2] The two-lever action of the moment arm is produced by the left arm in a right-handed golfer forming the upper lever moment arm linked by the wrist joint (which serves as a hinge), to the club shaft, which forms the lower lever. During the downswing, the left arm dictates the plane of the club then the right arm provides power in the latter part of the downswing. The downswing plane should be slightly more shallow than the backswing plane in order to strike the ball with maximum energy and precision.[2]

The right hip extensors and abductors and the left adductor magnus initiate left pelvic rotation during the forward swing,[40] although it has been proposed that there may be some left foot supination and lateral rotation of the patella prior to this movement.[2] Okuda et al.[41] has stated that eccentric action of the trunk muscles initiates the downswing sequence. The left pelvic rotation starts before the arms have completed the backswing.[10,40,41] In the downswing, the left arm externally rotates and moves toward the midline from the horizontally adducted position (the subscapularis and latissimus dorsi are very active in the forward swing phase with the pectoralis major becoming more active in the acceleration phase).[39] The right arm internally rotates and adducts and the elbow extends (the subscapularis, pectoralis major and latissimus dorsi are very active during both phases with an increased activity in the acceleration phase).[39,42] As the golfer rotates from right to left, the erector spinae muscles and the abdominal oblique muscles on the right side of the body act to maintain body posture[43] with both muscle groups becoming active on the left side of the body later during the acceleration phase. The wrists should remain cocked until the last moment if the two-lever one-hinge system is to work correctly in maximising the angular velocity of the club head. The left wrist uncocks by passive ulnar deviation while maintaining approximately 35° flexion, allowing the club head to rotate around the wrist joint in the direction of the target.[28]

Although golf coaches do not universally agree upon the role of wrist-cocking, recent evidence suggests that the cocking and uncocking of the wrists can significantly increase club-head velocity.[44-46] The degree of wrist-cocking when the lead forearm was parallel to the ground was significantly more in professional than amateur players,[44,45] indicating that the professional players held their wrists in a more cocked position at this phase of the swing. Using linear regression, Robinson[44] reported that of 15 kinematic/kinetic swing variables assessed, the degree of wrist-cocking was the strongest determinant of club-head velocity, accounting for 60.3% of the variance in club-head velocity between the golfers of varying ability. A computer simulation that modelled a golfer as a three-segment model (torso, left arm and golf club) gave an insight into the importance of wrist torque in driving the golfball. For a swing that produced a club-head velocity of 44 m/sec, wrist-cocking generated an additional 9% increase in club-head velocity at impact, as long as the torques were generated in a sequential proximal to distal order, with the wrist torque applied when the lead arm was approximately 30° below the horizontal.[46]

The kinetic chain action involves the initiation of the movement with the legs and hips followed by movement of the trunk and shoulders, and finally the hands and wrists. If executed correctly, the amount of kinetic energy is greater than the sum of the parts (i.e. there is summation of forces). Skilled swings use centrifugal force and conservation of angular momentum to gain maximum club-head speed at impact.[35] Average angular velocities for professional golfers have been recorded for the hip (498°/sec), shoulder (723°/sec), arm (1165°/sec) and club head (2090°/sec).[2] Optimisation calculations have confirmed that maximum club-head speed is achieved when the torque generators commence in sequential order from proximal to distal.[46] The linear contribution of joints to the golf swing has been determined using 3D analysis and suggests the major contribution from the wrist (70%) and shoulders (20%) with lesser contribution from the spine (5%) and hips (5%).[35]

At impact, the primary spine angle increases to approximately 34° compared with the 45° set-up angle and the secondary spine angle decreases to 28° compared with the 16° set-up angle.[47,48] At impact, shoulder rotation is approximately 27° and hip rotation approximately 43° to the left. The downswing phase creates an anterior shear force of up to 10% bodyweight on the right knee[10] and a vertical compression force of up to 80% bodyweight on the left leg during impact.[27] Mean peak forces and moments differ significantly between the lead and trail knees.[10,49] The left leg sustains large lateral (133N) and vertical (950N) compression forces and large rotatory torques (23 N • m) 0.02 seconds after ball impact.[27] Golfing ability affects the knee joint kinetics (peak knee joint loads) with larger forces in novice than elite golfers. However, footwear worn (spiked or spikeless shoes) does not affect these knee forces.[10,49] Budney and Bellow[38] reported that in the downswing the left then right hands applied force and at impact the left hand had firm control of the club and peak grip force (44N) with no force from the right hand.

2.1.4 Follow-Through

The purpose of the follow-through is to decelerate the body and club head by using eccentric muscle actions.[43] The hands and wrists follow the plane of the swing path. The left shoulder and arm abduct and externally rotate, and the right shoulder and arm adduct and internally rotate. When the hands reach shoulder level both elbows flex to decelerate the speed of the arms and the trunk rotation whilst maintaining postural stability. As the trunk and hips rotate to the left, the left leg internally rotates to absorb weight, and the left ankle supinates. The golfer should finish in a balanced position with the trunk facing the target in slight hyperextension and lateral flexion (there is abdominal oblique muscle activity for stability).[26,43,50] The hands should be behind the left ear and the head should be rotated to the left due to the turning trunk and swing momentum.

2.1.5 Ground Reaction Forces

Although the golf swing is often considered to be primarily an upper-body activity, a portion of the power of the swing is derived from the lower body.[10,49] To increase the GRF, the legs should be pushed down on the ground. To enhance the transfer of force, the body segments should be kept rigid (e.g. the trunk). In any throwing or hitting activity, a greater velocity of projection can be obtained if the player's momentum is travelling in the intended direction of the projectile's displacement. In golf, loading the back foot during the backswing and transferring this weight onto the front foot during the downswing and acceleration phases can achieve a greater club-head velocity at impact. Weight transfer has been shown to occur in numerous studies, with the transfer of bodyweight quantified by the GRF,[27,41,51] kinematic measures of the centre of mass position[31] or foot pressure fluctuations.[32,34,51-55] In order to maximise the club-head velocity at ball impact, considerable GRF must be produced.[33,51,56] When hitting a driver or 5-iron, vertical, anterior-posterior and medial-lateral peak GRF of 1.6–2.0, 0.4–0.6 and 0.2–0.3 bodyweights have been observed.[27,49,54] The magnitudes of these GRFs are comparable to those encountered while running at an average velocity of approximately 4 m/sec.[57] Significant differences in the magnitude of the transfer of bodyweight have been observed between golfers of varying ability. Kawashima et al.,[52] Koenig et al.[54] and Wallace et al.[53] all reported that during the backswing, low-handicap players had significantly greater GRF on the back leg than high-handicap golfers. In accordance with the weight transfer principle, low-handicap players produce greater GRF with the front foot during the downswing. Significant differences in the timing of these peaks relative to the various phases of the golf swing also exist.[27,49] Richards et al.[33] suggested that in order to effectively utilise the GRF, the timing and the magnitude of the transfer of bodyweight was more important than simply the magnitude of the GRF. What is evident from several studies is that the low-handicap players transfer more of their weight at a faster rate throughout the entire downswing phase.[34,41,53] However, Ball et al.[32,58] found no difference in distance between golfers who used transfer of momentum and those who didn't.

Taken collectively, these results suggest that in order to maximise the distance obtained with the driver and long irons, the golfer must produce considerable GRF. However, some evidence also suggests that a transfer of bodyweight from the back foot at the top of the backswing to the front foot during the downswing phases is also required to maximise distance. Consequently, professional players appear to more effectively utilise the momentum generated by bodily movements in generating power in the golf swing.

2.2 Stretch-Shorten Cycle and the X-Factor Stretch

The mechanisms underlying the improved power in SSC then concentric-only actions remain controversial,[59] yet the supposed action of stretching then contracting (shortening) a muscle/muscle group within a short time should increase elastic energy to enhance work and efficiency in the concentric action.[59] There may be a negative effect on performance of imposing a delay during a SSC movement.[60]

The 'modern' golf swing can be described as a powerful SSC activity, in which the muscles of the lower, mid-section and upper body are rapidly stretched prior to shortening. In order to effectively use the SSC in an attempt to hit the ball a greater distance, the golfer must stretch the muscles predominately causing the motion. While the mechanisms underlying the improved power in SSC then concentric actions remain controversial,[59] the effective utilisation of the SSC will enable the golfer to obtain greater distance.

In a SSC, the greatest enhancement of performance is seen when the rate of stretch (i.e. backswing velocity) is high. Professional players generally utilise a longer backswing amplitude (greater angular displacement) and accomplish this movement in less time than their amateur counterparts, ultimately increasing the velocity of the backswing and hence the rate of stretch.[28,47] However, the augmentation in performance gained from stretching a muscle is lost the greater the pause between the eccentric and concentric phases (in this case the backswing and downswing).[60] Golfers should attempt to move immediately into the downswing phase once the top of the backswing has been reached. As the left shoulder complex supplies a large portion of the power of the golf swing[42,61] it is vital that the shoulder is stretched in the backswing. The hip also provides some power for the stroke,[31] hence the trunk muscles should also be stretched. Therefore, the golfer should ensure that their backswing provides a sufficient rate of stretch of these major muscle groups and that the pause between the backswing and downswing is minimised.

While stretching the hip, trunk and shoulder musculature in the backswing enables the golfer to utilise the SSC, it appears that how the shoulder turn is achieved may be more important than the magnitude of shoulder turn in terms of maximising clubhead velocity. McLean[62,63] proposed that the differential between the hip and shoulder turn (i.e. the X-factor) at the top of the backswing, was more important than the absolute shoulder turn. In support of this view, McLean[62] demonstrated that the greater the absolute or relative X-factor, the higher a professional golfer was ranked on driving distance. Specifically, five of the longer hitting professional golfers (average ranking of 19 for driving distance) had absolute and relative X-factors of 38° and 43%. Five of the short hitters (average ranking of 161 for driving distance) had absolute and relative X-factors of 24° and 27%. In an attempt to replicate and extend the findings of McLean,[62] McTeigue et al.,[47] investigated the effect of age and playing standard on the X-factor by assessing 51 Professional Golf Association (PGA) professionals, 46 senior PGA professionals as well as 34 amateur players with a mean handicap of 17.5. While the X-factor for the PGA players (32°) was similar to that reported by McLean[62] the values were not significantly different to the X-factor of senior PGA (29°) and amateur players (34°).[47]

Due to these apparent inconsistencies in the importance of the X-factor in determining driving distance, Cheetham et al.[64] sought to determine how the X-factor may change throughout the swing in ten professional and nine amateur (average handicap of 15) players and at what point of the swing did intergroup differences in the X-factor occur. Although Cheetham et al.[64] reported that the X-factor at the top of the backswing was 11% greater in the professional than amateur players, this did not reach statistical significance. When maximum X-factor during the downswing (X-factor stretch) was compared, professional golfers had significantly (19%) greater X-factor stretch in the early phase of the downswing than the amateur players.[64] Therefore, the results of Cheetham et al.,[64] McLean[62] and McTeigue et al.[47] suggested that while the X-factor at the top of the backswing may have contributed to greater driving distance, the magnitude of the X-factor stretch seen in the early phase of the downswing may be of even greater importance to achieving maximum driving distance.

The significant increase in X-factor stretch observed by Cheetham et al.[64] in the early phase of the downswing was a result of the professional players beginning the downswing by rotating their hips back towards the hole. This is commonly referred to as leading with the hips. Initiating the downswing with the hips tends to be most pronounced in professional and low-handicap amateur golfers[31,45,47] According to the results from a 3D analysis,[31] low-handicap golfers' shoulders tended to rotate in excess of 90° during the backswing and continued rotating away from the flag as the hips began turning back towards the flag. Continuing to turn the trunk away from the hole while leading with the hips would result in a further increase in the X-factor stretch. By increasing the X-factor during the early phase of the downswing the golfer is able to utilise the summation of forces (velocity) principle in addition to better utilisation of the SSC. The sequential pattern of hip and shoulder rotation conforms to the summation of forces principle that should result in a greater torque being applied to the club before impact. The centre of mass shifting in the intended direction of ball flight during impact also benefited the speed of the drive.[31]

Table I summarises the literature on X-factor and golf performance. It should be noted that there were a variety of techniques used to calculate X-factor, which may have added to the variability in the results reported in the various studies. The X-factor values reported by Burden et al.[31] appear greater than the other studies.[47,62]

2.3 Maximising Ball Displacement with Physical Conditioning

It is commonly believed that specific strength and conditioning programmes may be able to improve performance in many sports, including golf. In relation to golf performance enhancement, the major proposed benefit of a conditioning programme is thought to be increased shot length – especially of the drive, through increasing the joint range of motion,[19] strength and muscle power,[65-67] muscle balance, and muscular and aerobic endurance. Consequently, a number of studies have assessed the effect of conditioning on golf performance (see table II).

A number of performance measures related to driving distance have been significantly improved

Table I. X-factor and golf performance. All results are mean ± standard deviation (where reported)

Study	Subjects[a]	X-factor	X-factor stretch	Performance variable
Burden et al.[31]	8 amateur male handicap = 7	70 ± 20°		
Cheetham et al.[64]	(1) 10 male PGA (2) 9 male amateur with 15 handicap	11% greater in PGA than amateur	19% greater in PGA than amateur	
McLean[62]	(1) 5 PGA long hitters (2) 5 PGA short hitters	(1) 38° (2) 24°		Average ranking for driving distance on PGA tour: (1) 19 (2) 161
McTeigue et al.[47]	(1) 51 male PGA (2) 46 male senior PGA (3) 34 amateur males with 17.5 handicap	(1) 32° (2) 29° (3) 34°		Downswing times: (1) 1.09 sec (2) 1.03 sec (3) 1.28 sec*

a PGA golfers playing off scratch or better.
PGA = Professional Golf Association; * indicates $p < 0.05$.

after approximately 8 weeks of general strength and flexibility training. Specifically, a combined programme of strength and flexibility training has resulted in significant increases in 5-iron distance,[70] rotational trunk power[69] and club-head velocity.[37,68,70,71] Overall, these results may suggest that conditioning programmes that incorporate strength and flexibility training or flexibility training alone may have a positive effect on golf ability. However, three areas of concern need to be addressed in relation to the effectiveness of conditioning training for increasing hitting distance in golf. First, no control groups were used in several studies that reported significant improvements in driving distance,[37,68,71] therefore, the modest improvements in performance seen in the experimental groups may potentially be within the expected inter-day variation in performance attributed to the natural variation in the output of the measuring device, improved subject familiarity with the testing procedures or environmental conditions. Secondly, with the exception of Jones,[68] all of the studies that reported significant improvements in measures related to driving distance used concurrent strength and flexibility training. Although the strength-training component of these programmes was generally emphasised over the flexibility component, this mixed research design does not allow the practitioner to delineate the relative effectiveness of strength or flexibility training in improving driving distance. Finally, these research studies were conducted with junior (<18 years) or senior (>50 years) male golfers, so it is unknown what the effect of strength and flexibility training would be on open-age male golfers or female golfers of any age. In addition, these studies have consisted of non-specific (general) weight-training exercises.

A strength training programme that incorporates training exercises that are more specific to the golf swing in terms of the movement patterns, velocity and posture may induce greater improvements in performance than that seen in the literature. With this view, a number of computer simulations have investigated what effect an increase in torque would have on the club-head speed just prior to ball contact, and hence ball displacement. Within this framework, Reyes and Rittendorf[72] and Sprigings and Neal[46] have both demonstrated that greater torque will result in an increase in club-head speed just prior to ball contact, and hence ball displacement. These results indicate that an increase in muscular strength/power can increase the distance of a golf shot, as long as all other factors remain equal.

Computer simulations[72] and experiments with golfers[19] have demonstrated that increasing the length of the backswing will result in greater distance off the tee. Consequently, high-level golfers have been reported to perform extensive flexibility training on a regular basis. Jones[68] attempted to determine the effectiveness of proprioceptive neuromuscular facilitation stretching on club-head velocity of the driver at impact. Sixteen golfers performed proprioceptive neuromuscular facilitation stretches for the total body for a period of 45 minutes, five times per week for a duration of 8 weeks. At the conclusion of this training period, there were significant improvements in hip flexion and extension, shoulder abduction and external rotation and trunk rotation. These improvements in range of motion were in the order of 7.1–35.3% and resulted in 7.2% improvement in club-head speed from 124.41 to 133.38 km/hour. However, a number of questions still remain unanswered from this study as no control group was assessed. Even though the increases in flexibility appear greater than that expected by chance, it can not be conclusively shown that the proprioceptive neuromuscular facilitation programme was responsible for the increase in flexibility and club-head velocity. Additionally, the mean age of the golfers was 58 ± 9 years, therefore, it is unknown if the same change in flexibility and club-head velocity would be observed in young players who are known to possess greater flexibility.[73]

In summary, when the golfer wants to maximise the distance of their swing shots, current research suggests that the golfer should: (i) produce large GRF (with proportionally more GRF on the back foot during the backswing and transfer these GRFs on to the front foot during the downswing/acceleration phase); (ii) rapidly stretch the muscles of the hips, trunk and upper limb during the backswing; (iii) maximise the X-factor early in the downswing so as to take advantage of the summation of force principle; and (iv) uncock the wrists when the lead arm is about 30° below the horizontal. Physical conditioning programmes that increase strength and increase joint range of motion can help to increase golf driving distance.

2.4 Kinematics and Kinetics of Putting Shots

In contrast to swing for distance, the primary goal of putting is to hit the ball very accurately over a relatively short distance; the maximisation of power and distance is not a required quantity for these activities. Therefore, successful putting relies on the ability to hit the ball accurately with the required power so that the ball comes to rest close to the hole.[74] According to Wiren[29] this ability to putt well may be affected by the type of grip chosen, the ability to read the green (aiming), club-head velocity (magnitude and direction) at impact, the position of the club head relative to the upper body, and the contact point between the ball and the club.

While a large number of studies have investigated factors related to successful putting, only a relatively small number have been from a biomechani-

Table II. The effect of conditioning programmes on golf performance. All results are mean ± standard deviation (where reported)

Study	Subjects	Training type	Duration (wk)	Frequency (d/wk)	Change in performance
Hetu et al.[37]	n = 17; age 52.4y; HCP?	Strength and flexibility	8	2	Increased club-head velocity
Jones[68]	n = 16; age 58 ± 9y; HCP 18 ± 7	PNF stretching	8	3	+7.2% club-head velocity*
Larkin et al.[69]	n = 4; age? HCP?	Strength and flexibility	3	?	+45% trunk rotational power*
Larkin et al.[69]	n = 4; age? HCP?	Control	3	0	+7% NS trunk rotational power
Lennon[70]	n = 7; age 16 ± 4y; HCP?	Strength and flexibility	8	4	+5-iron distance*[a]
Lennon[70]	n = 7; age 16 ± 4y; HCP?	Control	8	0	NS (5-iron distance)[a]
Westcott et al.[71]	n = 17; age 57y; HCP?	Strength and flexibility	8	3	+6% club-head velocity*
Westcott et al.[71]	n = 5; age? HCP?	Control	8	0	0% NS club-head velocity

a Although significance was discussed, no actual distances were reported.

HCP = handicap; **NS** = non-significant ($p > 0.05$); **PNF** = proprioceptive neuromuscular facilitation; **+** indicates increase; ***** indicates $p < 0.05$; **?** indicates unknown.

cal viewpoint. These studies have typically assessed a number of kinematic and temporal variables of the putt in golfers of varying ability. For example, Paradisis and Rees[75] assessed putting kinematics of low-handicap and high-handicap players with putts of 2.46m (8 feet). Of the 26 kinematic parameters measured, significant differences between the groups were observed on nine variables. The low-handicap players utilised a proportionally smaller backswing and follow-through than high-handicap players, even though the distance of the putts were equal in both groups. The novice golfers vertical displacement of the club head during the backswing and follow-through was far greater than the expert golfers. The greatest velocity occurred at ball impact or just after for the expert golfers, but the timing of maximum velocity was more erratic for the novice golfers. Low-handicap players positioned their leading hand almost 8cm further down the shaft of the club than the high-handicap players.[75] According to Leadbetter,[76] this lower hand placement would allow the low-handicap players to lock their wrists into a firmer position, minimising movement at the wrist, and improving the consistency in putt direction and velocity at impact.

Delay et al.[77] sought to assess the effect of golfing ability on putting kinematics, in particular the ability to correctly specify the required force for a number of short putts. Ten expert golfers and ten non-golfers were required to perform ten 'correct' trials at each distance (1m, 2m, 3m and 4m), where a 'correct' trial was a putt that stopped within a distance of 5% of the hole. With increasing putting distance, the golfer must generate greater club-head velocity at the moment of contact with the ball. Downswing amplitude was significantly larger for expert golfers than for non-golfers (671 vs 520mm). Movement time was significantly shorter for the non-golfers than the expert golfers (563 vs 709ms). Club velocity on contact with the ball was significantly higher for the non-golfers than the expert golfers (1.5 vs 1.3ms). The path of the club was almost parallel to the plane of the green for the expert-golfer but curved for the non-golfer. The expert golfer also initiated the movement closer to the ball and finished at a position lower on the ball than the non-golfer.

Fairweather[78] examined five experienced golfers capability to cope with variable distances and green conditions in order to examine motor control and transfer issues in putting. The golfers controlled the distance through which the putter head travelled in line with putter distance requirements. In other words, the golfers scale the length of the backswing to putt across different distances;[77-81] however, the duration of the downswing is also altered. For long putts, players increase the length of the backswing and decrease the duration of the downswing compared with short- or mid-length putts.[78,80] This indicates that the player attempts to control the acceleration of the club during the putt rather than simply adjusting backswing amplitude whist keeping movement duration constant.[78] This is consistent with learners progressing from controlling positional parameters to force-related parameters.[78] Craig et al.[80] developed a model to predict how golfers regulate spatial and temporal components of the forward swing in order to transmit the appropriate amount of kinetic energy at ball impact. The principles of the model involve guiding movement by coupling them onto intrinsic perceptual information about the measure of a gap and spatially scaling the movement by changing the amplitude of the downswing or changing the duration of the swing.

The starting position rather than the final position of the ball plays a crucial role in the on-line visual control of golf putting. Coello et al.[79] conducted a kinematic analysis of the downswing for five expert golfers when vision of the club was either allowed or occluded during the movement execution. Downswing amplitude was significantly shortened (184.2 vs 239.5mm) and velocity at impact was smaller (1.2 vs 1.6 m/sec) in the restricted vision condition compared with the full vision condition. The downswing duration was not affected by visual condition. Therefore, visual information of the initial position of the ball is required to drive the golf club to the expected final position of the ball with the required final velocity. Given that club orientation must be precisely adjusted to avoid a change in trajectory of the ball, there is a high demand for visual information when accuracy is required.[79]

Sanders[74] investigated the kinematics and kinetics of putting and how changes in these factors were related to putting performance in two amateur players of unknown ability. The club-head velocity and torque due to the hands from the start of the downswing to the ball impact for Jack Nicklaus was used as an expert model. Consistent with Paradisis and Rees,[75] Sanders[74] showed that prior to their coaching sessions, both players had positive club-head acceleration at the point of impact. The player who received graphical feedback on club-head velocity and hand torque improved their putting performance by decreasing club-head acceleration at the point of impact more than the other player. Both players improved their putting performance with the 4 days of coaching (half an hour per day). While based on only two players, with the expert for comparison, these results suggest that by reducing the wrist torque near ball contact, the club-head velocity at ball impact was less variable, thus enabling the golfer to more consistently apply the desired level of force to their putts. Constant velocity of the club head throughout the period of contact would help to achieve consistency with the length of the putt. Letting gravity start the movement of the putt from the top of the backswing, applying torque with the hands and then stopping the application of hand torque near the time of ball impact would ensure that the club head coasted through the impact with a constant velocity.[74]

Carnahan,[82] in an experimental study of the effects of distance, slope and break on putting performance, showed that a strategy of playing an approach shot to leave a short predominantly uphill putt resulted in more successful putting. Strokes are more likely to be lost by high-handicap players when playing from longer distances.[83] The 7.3m (24-foot) distance is important to consider when assessing the control characteristics of the putting action. It is at this distance that clear differences in scoring success emerge across the handicap range,[83] therefore, players should practice more from long distances.

Professional and amateur golfers use two styles of putters with the conventional length putter being more common than the long (broomstick) putter. Both putters can produce similar results.[84] However, the long putter has been more effective on 0.9m (3-foot) putts, equal to the conventional putter on 2.7m (9-foot) putts and less accurate on 6.1m (20-foot) putts[85] and 12.2m (40-foot) putts.[86]

In summary, when the golfer wants to maximise the accuracy of their putting shots, the golfer should produce a lower grip on the club and a slower/shorter backswing for superior putting performance. There have been inconsistencies in the findings surrounding the maintenance of a constant club-head velocity at impact and maintenance of a follow-through length equal to the length of the backswing. Professional golfers show more consistent patterns of shoulder and wrist movements and temporal patterning of their chip shots than novice players.

3. Methods Used to Biomechanically Assess Golf Technique

3.1 Qualitative Golf Biomechanics

Qualitative biomechanics provides the golf coach/biomechanist with the ability to observe a golf skill being performed, evaluate its effectiveness and supply appropriate feedback to the golfer. The qualitative biomechanics approach provides the main purpose of the golf skill, divides the skill into meaningful phases (preparation, execution and follow-through), provides the main purpose of each of the phases, identifies the key elements within each phase (important individual actions within a skill performance that influence the final outcome), which leads to the development of an observation plan to analyse all the key elements. The biomechanist has a theoretical model of how the skill should be performed based on mechanical principles. The observed skill is then compared with the theoretical desired performance and the cause of any problem is determined. It is important that the biomechanist determines the cause of the problem as opposed to just identifying the effect. Once the problem is defined, the biomechanist then determines how to fix the deviation from the desired result.

The preparation phase contains all movements that prepare the golfer for performance of the skill (e.g. the set-up, which may be explained by the address). The execution phases involve the performance of the actual movement (e.g. the golf club backswing and the downswing to ball contact) and the follow-through phase refers to all movements occurring after the execution phases (e.g. deceleration of the club head after ball contact). The key elements in each phase must refer to specific body movements and must be observable. The observation plan indicates what angle the skill will be observed from, what parts of the body will be looked at initially, and how many times the skill will be observed.

The biomechanist and coach need to consider that each athlete will have different anatomy, athletic background and level of efficiency. Different stages of growth and development will strongly affect ability, and therefore the key elements may differ depending on the age and development stage of the golfer. The coach must also be aware of factors that influence performance such as the golfer's fatigue, anxiety levels and the environmental conditions. The skill should be observed in a manner closely related to competition.

During initial observation, the biomechanist will first focus on the entire movement to gain an overview of the golfer's performance, then will begin to focus on individual performance phases and individual key elements. Outer extremities and the club move at a rapid pace so a biomechanist will video the movement and analyse the skill in slow motion. If a video is not available then the biomechanist will focus firstly on slower moving parts (e.g. hips and trunk) that are generally located close to the centre of mass and then shift focus to the arms and hands.

There is no set number of trials that should be observed. This will depend upon the skill level of the golfer, the skill level of the observer (coach/biomechanist) and the effects of fatigue if the skill has been performed many times. A skill must be focused on long enough so that it is evident that the skill is being performed at a consistent level.

Wiren[29] has described a golf teaching model called 'laws, principles and preferences' to describe the golf swing. The laws are the mechanical definitions, with the principles and preferences allowing a player to achieve the laws. The laws described by Wiren (and other authors) are club-head speed, centeredness of contact, club-head path, and position of clubface and angle of approach. The principles are grip, aim, set-up, swing plane, width of arc, length of arc, left wrist position, lever system, timing, release arc, dynamic balance, swing centre (rotational), connection and impact. Preference examples are early wrist-cock, two-knuckle grip, outside takeaway, flat backswing, cupped left wrist, left toe out, fixed centre, high hands, slow back, open stance, lateral slide, light pressure, bent left knee, extended arms, chin behind, weight forward, shoulder closed. Wiren's golf teaching model uses a mixture of biomechanics principles and the art of coaching.

Coaches' perceptions of golf swing kinematics have been assessed by Sherman et al.[87] who used a computer-based videotape analysis system to present a randomised series of golf swings to ten coaches of professional golfers and ten coaches of amateur golfers. The two coach groups had similar ability in identifying fundamental characteristics of the golf swing, but their model of the ideal swing was influenced by the observed golfer's skill level. Therefore, it is important that coaches have a good understanding of the biomechanics of a golf swing so their assessment can be based on sound mechanical principles rather than subjective judgements of skill level. Figure 1 shows a deterministic model of the golf swing that allows the coach and biomechanist to focus on the fundamental biomechanical characteristics important in achieving large distance in a drive shot.

3.2 Quantitative Golf Kinematics and Kinetics

Quantitative kinematic golf biomechanics provides numerical data on the body angles and move-

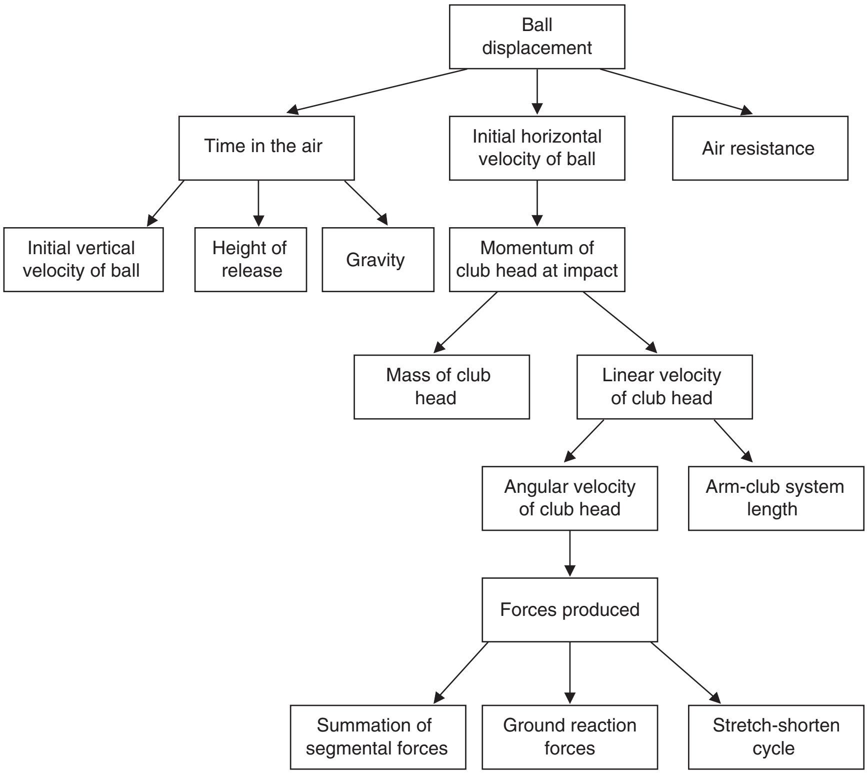

Fig. 1. A deterministic model of the golf swing showing biomechanical factors related to achieving large distance in a drive shot.

ments during the golf swing. These angles are usually gained from video analysis where a video image is captured onto a computer and a programme determines the angle by a process called digitising. Golf is a 3D movement, therefore, 3D analysis is preferred for golf research.[73] However, correctly aligned cameras using two-dimensional (2D) methodology can provide important information on joint alignment and provide useful feedback for learning the golf swing.[88] Two important angles for a golfer are the primary spinal angle (angle between the thighs and trunk from the sagittal view) and the secondary spinal angle (shoulder tilt resulting from a combination of lateral bending in the spine and slight depression and downward rotation of the arm and scapula during the backswing).[2] The X-factor (differential between the hip and shoulder turn) is also considered important for golf.[62,63] In addition to the more common video analysis, lightweight triaxial electrogoniometers and the Swing Motion Trainer (a device that utilises rate gyroscopes and potentiometers) have also been used to assess spinal motion in golfers.[47,89] Golfers with low-back pain tended to flex their spines more when addressing the ball and exhibited greater lateral flexion on the backswing.[89] Pain-free golfers had twice as much trunk flexion velocity on the downswing than golfers with pain.[89]

Quantitative kinetic golf biomechanics provides numerical data on the internal and external forces during golf movements. Force platforms are used to assess the GRF and inverse dynamics uses force data synchronised with video data to estimate joint compression force, shear force, and muscle moments and joint powers. Pressure systems are used to assess pressure distribution in the feet during golf movements.[27,34,53,58,90] Electromyography (EMG) is used to assess muscle timing and when normalised to a percentage of maximum voluntary contraction, can be used to estimate the relative importance of various muscles to the golf swing.[13,26,91-94] EMG studies have shown that both arms are active throughout the entire swing and contribute to the development of club-head speed during the downswing.[28,39] Other EMG studies have shown that hip and knee muscles,[40] trunk muscles,[43,95] scapular muscles[96] and shoulder muscles[61,92,93] all contribute to the golf swing.[41] The effects of skill level on muscle activity in the neck and forearm during the golf swing have been examined.[91] EMG has also been used in combination with videography to assess spinal loads in golf.[97,98] Computer simulation and optimisation models have also been used to describe and predict a variety of golf movements.[46,72,98,99] Laser speed guns and high-speed videos are used by golf ball and golf club manufacturers to assess impact characteristics between the club and the ball, and the nature of the ball flight.

4. Golf Biomechanics Terminology and the Effects on the Ball and the Club (Head, Shaft, Grip)

Golf biomechanics terminology refers to balance, body centre of mass, base of support, displacement, velocity, acceleration, Newton's laws of motion (inertia, acceleration, action reaction), the kinetic link principle and segmental coordination and sequential summation of forces, torque and lever arms, projectiles and the SSC.

4.1 Balance, Body Centre of Mass and the Base of Support

The force of gravity moves vertically through the body's centre of mass (an imaginary point representing the balance point of the body). This line is referred to as the line of gravity. Balance is improved if the line of gravity passes through the centre of the base of support (provided by the area bounded by the feet on the supporting surface), if the height of the body's centre of mass is lower relative to the base of support, and if the centre of mass is kept rigid rather than wobbly (stable pelvis and abdominal region). Therefore, in order to increase stability during a golf shot, the feet should be shoulder-width apart with the line of gravity of the centre of mass within the trunk over the base of support (feet) and the postural muscles in the pelvic and abdominal region active. Golf coaches refer to both dynamic and static balance where static balance is being able to maintain a balanced body position (i.e. set-up) and dynamic balance is the ability to transfer weight correctly in the swing.[3]

4.2 Displacement, Velocity and Acceleration

Displacement (length and direction) of a golf shot are vital components of success in golf. Displacement of the golf ball is related to the amount and direction of the force applied to the golf ball by the club head and the resistance to motion of the medium through which the ball travels (e.g. air, grass). The ultimate displacement of the golf ball is a function of the linear club-head velocity at ball contact, where linear velocity equals the change in linear displacement (position) over the change in time. This linear velocity of the club head is in turn the product of the angular velocity of the club head and the length of the lever (i.e. the arm-club system). The angular velocity of the club head is equal to the change in angular displacement of the club head over time.

4.3 Force and Newton's Laws of Motion

By definition, the application of a force results in a change in motion or shape of an object. While the magnitude of the force is important, the biomechanist also needs to know the direction and point of application as well as the time the force was applied over in order to quantify the effect of the force on an object's motion. One Newton (N) of force is required to give a mass of 1kg an acceleration of 1m per second per second (m/sec/sec).

Forces can be described as being internal (muscular forces acting within the body) or external (acting on a body such as the GRF). There are three types of internal muscle forces: (i) concentric – where muscles shorten while developing tension; (ii) eccentric – where muscles elongate while developing tension; and (iii) isometric – where muscles produce tension with no change in muscle length.

Knowledge of each of these types of internal forces is important when prescribing physical conditioning exercises for golf. GRFs are a result of gravity acting on an object on the ground – the golfer's body has a force on the ground and the transfer of the bodyweight force during a golf swing can be measured using the GRF. GRFs and torques of professional and amateur golfers have been measured.[27,31,46,56]

There are various types of external forces in golf. Friction is a contact force existing between bodies. Friction acts along the common surface (i.e. the green) and in a direction that opposes any motion of the body (e.g. the movement direction of the golf ball is opposite to the friction force of the green). Centrifugal force is developed with rotary motion of the club head, with linear motion imparted to the ball at point of impact.[2]

The relationship between the kinetics and kinematics of an object are described in Newton's three laws of motion. All three of these laws relate to how golf is played. Newton's first law (the law of inertia) states that a body (i.e. the golf ball) will remain at rest or continue in a state of uniform motion in a straight line unless it is acted upon by an external force (e.g. the golf club, gravity, wind resistance or friction from the grass). Inertia is the reluctance of a body to alter its state of motion. Linear inertia is measured solely by the mass of the object while angular motion inertia (moment of inertia) is proportional to the object's mass and the square of the distance between the point of rotation and the centre of gravity of the object. For example, in a backswing in golf, the angular motion has inertia caused by the mass of the golf club and the distance of the golf club mass from the centre of gravity of rotation that is located around the lower trunk region. The larger an object's mass the harder it is to start moving the object or to change its direction or velocity (e.g. think of hitting a ping-pong ball versus a golf ball with a feather).

Newton's second law, known as the law of acceleration, states that the rate of change of momentum of a body (i.e. the golf ball) is directly proportional to the magnitude of the applied force and acts in the direction of the applied force (F = m [kg] * a [m/sec/sec]). Consequently, if a large force from the golf club is applied to the ball, the ball will undergo a large change in momentum. According to the law of conservation of momentum, the total momentum of the ball and club head is neither created nor destroyed. Therefore, the initial velocity of the golf ball at impact (v_{ball}) will be equal to the velocity of the club head (v_{CH}) multiplied by the ratio of the mass of the club head (m_{CH}) to the mass of the ball (m_{Ball}), as seen in the following equation.

$$v_{ball} = v_{CH} \times \frac{m_{CH}}{m_{Ball}} \qquad \text{(Eq. 1)}$$

The law of conservation of angular momentum can also be applied to the golf swing as speed is transferred from the hands to the club head.[2] At the beginning of the downswing the hands move the fastest with the club head moving the slowest. Near impact, the hands decelerate and transfer the momentum to the club head that will then accelerate, ultimately leading to high club-head linear velocity and ball displacement.

For every action force there is a reaction force that is equal in magnitude but opposite in direction. Newton's third law is often called 'the law of action and reaction'. Forces never act by themselves, they always act in pairs. Impulse is the force multiplied by the time over which the force acts. Changing the motion over a shorter period of time can increase forces in impact.

4.4 Projectiles

When flying through the air, a golf ball is considered to be a projectile, so that the centre of gravity of the ball follows a parabolic trajectory. The path of this parabolic trajectory will be dependent upon the angle, height and velocity of release of the ball just after impact by the club. As soon as the projectile is airborne, gravity acts to change the motion of the ball (reduce the vertical velocity), so that the golf ball must return to earth. Similarly, the wind (air) resistance also acts to change the motion of the ball, generally resulting in a reduction in horizontal velocity that ultimately reduces horizontal displacement. Spin imparted to the ball at impact will affect the rate of rotation of the ball and the way in which the ball interacts with the air. The Bernoulli effect describes the rotation effect of a ball when there are differences in air pressure around the ball surface. The Bernoulli effect accounts for the slice and curve motions of the ball. The dimples on a golf ball affect the turbulent and laminar flow of the air around a ball and can be described by the Reynolds number.

4.5 Torque and Lever Arms

The tendency of a force to cause rotation around a pivot point is called torque, where the magnitude of the torque is equal to the product of the force and the lever arm (i.e. the perpendicular distance from the point of rotation to the line of the force). Therefore, the length of the arm-club lever at the point of impact will have a direct result on the velocity of the ball. A 3D analysis of the forces and torques applied by a golfer during the downswing has been described.[56]

4.6 Kinetic Link or Sequential Summation of Forces Principle and Segmental Coordination

The kinetic link and sequential summation of forces principle states that in order to maximise the velocity of the most distal segment (i.e. the club head), the movement should commence with the larger, proximal segments (e.g. hips and trunk) and proceed in a sequential manner to the smaller, more distal segments (e.g. upper arm and hands).[41] Consequently, the golf swing is a complex action that requires the coordinated activity of numerous muscle groups in order to be completed correctly[42] and so that maximum velocity is obtained.[41] This sequential pattern of hip and shoulder rotation is an example of the 'summation of speed' principle, which is hypothesised to result in a greater torque being applied to the club before impact.[31] An optimisation process using a 2D, three-segment model comprising torso, left arm and golf club to characterise the downswing confirmed that maximum club-head speed was achieved when torque generators commenced in sequential order from proximal to distal. The club-head speed at impact could be further increased by an optimally timed wrist torque without jeopardising the desired club position at impact.[46] This wrist torque is commonly referred to as uncocking the wrists prior to ball contact.

In summary, both qualitative and quantitative biomechanics provides the golf coach/biomechanist with the ability to observe and describe a golf skill being performed, evaluate its effectiveness and supply appropriate feedback to the golfer. Knowledge of biomechanics principles and appropriate interpretation and application with respect to golf technique has the potential to improve golf performance and reduce the risk of injury.

5. Conclusions and Recommendations

An understanding of correct technique should help the sports medicine practitioner provide technique advice and should help reduce the risk of golfing injury. Biomechanics has a role in maximising the distance and accuracy of all golf shots (swing and putting) by providing both qualitative and quantitative evidence (e.g. body angles, joint forces and muscle activity patterns). The biomechanical quantitative data need to be interpreted by the biomechanist and translated into coaching points for the golf professionals and coaches.

Research should focus on predictors of golf technique for golfers of varying physical characteristics to improve golf performance and reduce the risk of injury. Biomechanics technology and approaches should be used to help enhance performance in golf.

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