Monitoring Performance in Golf: More than just Clubhead Speed

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Abstract

In the golfing literature, clubhead speed is the most commonly reported metric to assess golf performance. However, a rise in the availability and use of launch monitor technologies in recent years has gathered a wide range of metrics for any given golf shot. In addition, with distance and dispersion (accuracy) being the outcome measures of any given shot and of utmost importance in golf, launch monitors can provide an in-depth understanding of how a golf shot has been achieved. To date, very limited information offers practitioners working in golf an understanding of how these metrics interlink and relate to the outcomes of any given shot. Thus, we have created a deterministic model for the golf shot and provided an overview of the relationship between these launch monitor metrics and the outcome measures of distance and accuracy. This information will give practitioners a more detailed understanding of how golf shots have been achieved and help provide more methodical means of monitoring golf performance and providing feedback to players.

Key Words: Launch monitors; distance, dispersion.

Introduction

There has been a surge in the number of participants playing golf in recent years, with an estimated 55 million people playing golf worldwide at the turn of the 21st century (36) and upwards of 30,000 golf courses globally to facilitate playing the sport (16). Professional golf is split between the US Professional Golfers Association (PGA), DP World Tour, and recently LIV Tour for males and the Ladies PGA Tour and Ladies European Tour for females. However, there are also several additional professional tours elite golfers can participate in, such as the: Asian, Canadian, and Sunshine Tours, to name a few. The underlying aim of golf is to get the ball in the hole in as few shots as possible. Elite professional golfers and competitive amateur golfers will compete to the par of the course being played and subsequently achieve a score from the number of shots taken across any given round. Performance is scored slightly differently during recreational and less competitive golf, as players are given a handicap index, which provides them with a shot allowance relative to their skill level. Professional golf uses a "gross" score, with no adjustment on the final scoring, while recreational golf often uses a "net" score, which is adjusted for that player's handicap index. Beyond an individual's skill level, the handicap index also considers factors relating to the difficulty of the course, such as the length of each hole, course rating, and slope. Given the wide range of abilities, several authors have looked to classify golfers relative to skill level. For example, previous research has suggested that golfers with a handicap index < 10 are regarded as 'highly skilled' and those with a handicap > 10 are regarded as 'lesser skilled' (15). However, this distinction has been suggested to be an over-simplification, with other authors suggesting three different classifications: 1) elite (professional players competing on tour or amateurs competing in international or national amateur championships), 2) sub-elite (PGA teaching professionals, amateurs competing in regional, county and state tournaments, or with handicap ≤ 5), and 3) recreational (handicap > 5) (28).

Both golf score and handicap provide a general metric for golf performance; however, these metrics cannot break down the individual factors that may have contributed the most to performance. Technological advances have allowed professional organizations (i.e., PGA Tour) to collate a range of tournament performance statistics such as driving distance, driving accuracy, greens in regulation (GIR), and putts per round, to name a few (1,10,30). These metrics may provide some measure of the necessary skills that lead to a player's success or failure. For example, GIR is a measure of hitting the green in the requisite number of shots relative to the par of the hole while allowing two putts to make par. Therefore, on par 3 holes, one shot is available to get to the green, meaning performance off the tee will directly determine whether GIR has been achieved. On par 4 and par 5 holes, an additional one and two shots are allowed to make the green, respectively.

Consequently, combining a tee shot and approach shot(s) will determine GIR performance on par 5 holes. However, to contextualize the limitations of a metric like GIR, in 2020, Jim Furyk hit 74% GIR and was ranked first for this metric on the PGA Tour, but his total earnings were $185,000 for the season. In contrast, Rory McIlroy hit 68% GIR and was ranked 76 but earned $4.4 million for the season. Similarly, driving accuracy is determined, rather simply, by whether or not a player hits the fairway from their tee shot on par 4 and 5 holes. However, Broadie (9) has previously outlined that an extra 20 yards in distance will give players a distinct competitive advantage over others in competition by gaining, on average, 0.75 strokes per round.

Further, if a player's drive lands in the 'light rough', it is unlikely to cause a significant detrimental effect on the next shot. Thus, although this statistic provides some indication of the accuracy of a golfer's tee shot, it does not distinguish shots that miss the fairway by a small margin from shots that miss the fairway by a greater distance and potentially end up behind a tree, in the water, or out of bounds (17). Unfortunately, most golf statistics follow a similar pattern where they lack the description to isolate the specific skill that may contribute to performance due to issues related to shot location. Thus, many of the current performance statistics combine multiple technical skills and physical capacities, which do not uncover the more detailed contributions of swing performance. As such, a more in-depth analysis of golf performance is required to fully comprehend how and why a player is achieving performance on a given hole or round.

From a strength and conditioning (S&C) practitioners' perspective, the most commonly reported golfing metric is clubhead speed (CHS) (14,20,24,32), which is a key factor influencing shot distance. This is likely due to its strong association with physical characteristics such as strength (upper body, $r = 0.62$; lower body, $r = 0.91$) and power (upper body, $r = 0.71$; lower body, $r = 0.79$) (4,14). Furthermore, achieving maximal distance off the tee (on par 4 and par 5 holes) typically provides golfers with an advantage, assuming accuracy can be maintained (9,19). However, data relating to shot dispersion (accuracy) are less common in the golfing literature, despite the professional tours reporting dispersion data off the tee for all tournaments, ranking players on the percentage of fairways hit. Thus, distance and dispersion can determine the success of any given approach shot and, even more so, success off the tee (19). However, with distance and dispersion being the outcomes for any given shot, focusing purely on these metrics provides little context as to how either is achieved. Thus, to understand how distance and dispersion are accomplished, it is essential to understand the 'launch characteristics' of the ball.

Further, the interaction between the clubhead and golf ball at impact provides 'impact factors' that can explain the subsequent launch characteristics of the shot (25). At the elite level, launch monitor technologies, such as TrackMan, GC Quad, and Flightscope, are frequently used, providing practitioners with data on a wide range of metrics relating to distance and dispersion (25). The relevance here is that understanding the influence of these interactions will provide practitioners working with golfers with a methodical way to monitor golf performance metrics that link directly to shot outcomes and, ultimately, determine a golfer's score during competition (21).

Therefore, the primary aim of this review is to provide an overview of the existing literature on launch characteristics and impact factors related to the outcomes of distance and dispersion in golf. To support this, we have created a deterministic model for golf shot performance (Figure 1), which presents a framework for how these metrics will likely inter-link. Given that readers may not be entirely familiar with some of these variables, Table 1 provides a list of operational definitions for each of these variables from our deterministic model. We then provided two detailed sections on how some of these metrics may inter-link with shot distance and dispersion before providing a practical application section so that practitioners can consider how best to action some of this new information in their daily practice.

*** Insert Figure 1 about here ***

*** Insert Table 1 about here ***

Strokes Gained

Before discussing information relating to shot distance and dispersion, and given that the pinnacle of Figure 1 refers to strokes gained off the tee (SGOTT), readers should first understand this concept. Broadie (8) first established the performance measure described as 'strokes gained', which provides a measure of how many strokes a player 'gains' for each shot relative to their shot location compared to the competitive field. Simply put, this measure attempts to cut through the excess golf statistics by isolating a golf shot on how close the shot brings the golfer to 'holing out', thus indicating the quality of the golf shot (7). When Broadie developed strokes gained, two predictors of how many strokes it takes to hole out from a given position on the course were identified: 1) distance from the hole, and 2) the 'condition' of the shot (i.e., off the tee, on the fairway, in the sand or rough, on the green, etc.) (8). To calculate strokes gained, the starting and finish positions of any given shot are compared, and because one shot is always taken, one stroke gets subtracted from the equation. We have provided an example of how strokes gained can be calculated when a golfer on a 400-yard par 4 hole hits their drive to a position that finishes 120-yards away from the flag on the fairway (note: all forthcoming information has been previously calculated by Broadie (8) and is now used by the PGA Tour for in-tournament statistics):

1. From position one, 400-yards on the tee, PGA Tour professionals average 3.99 strokes to 'hole out'.
2. From position two, 120-yards away from the hole in the fairway, PGA Tour professionals average 2.85 strokes to 'hole out'.
3. Thus, position two (2.85) is subtracted from position one (3.99): (3.99-2.85) = 1.14.
4. The value of 1 (because 1 stroke is taken for any given shot) is then subtracted from our resultant value of 1.14: (1.14-1) = 0.14.
5. Therefore, the golfer's 280-yard drive into the fairway 'gained' 0.14 strokes, relative to the rest of the field.

As aforementioned, metrics such as the percentage of fairways hit and drive distance have been utilized to understand performance off the tee but have left a void regarding the interaction between drive distance and hitting more fairways. For example, should a golfer sacrifice distance to hit more fairways during a tournament and achieve a lower score? These are questions that isolated measures are commonly unable to answer. Hence, strokes gained and SGOTT provide a value that acknowledges the contributions of distance and dispersion off the tee, which can be related to launch characteristics and impact factors. Interestingly, Broadie (8) concluded that the long game (off-the-tee and approach shots) explains about 72% of the variability of a PGA Tour player’s overall skill (26). However, Broadie (7) also stressed that variability does not equate with importance. Therefore, strokes gained is a necessary means of understanding the game on a functional level. However, this metric is typically monitored during competition, which limits our ability to use it during training and preparation periods, when S&C practitioners are likely to have the most contact and influence with their players. Furthermore, the metrics presented in this review, relative to the clubhead impact and ball launch characteristics, provide primary metrics for analyzing performance off the tee, which are likely to be of more importance for S&C practitioners, given the improvements we are likely to be able to make in measures such as CHS (15).

Shot Distance

Achieving maximal distance off the tee will place a golfer closer to the hole, which, although hole-dependent, is likely to improve their chances of getting closer to the green and holing out in fewer shots (9). As presented in Figure 1, achieving maximal distance is a complex relationship between clubhead impact factors and ball launch characteristics when environmental factors and ball technology are negated. The upcoming section will review the current literature to highlight the primary impact factors and launch characteristics that influence shot distance.

A study by Betzler et al. (2) analyzed the effects of clubhead presentation on golf ball launch conditions and subsequent shot outcome in 285 golfers of different playing abilities (handicap: male = 9.1 ± 6.4; females = 15.3 ± 9.9). Findings showed the importance of ball speed on shot outcome, whereby an increase in 1 mph resulted in a subsequent increase of 1.83-yard carry distance (2). Linked to this, the most apparent association with ball speed is CHS (18-20,24). For example, Sweeney et al. (35) reported that CHS alone explained 75% of the peak resultant ball speed variance. Theoretically, if the clubhead travels at a greater velocity, the ball will leave the clubface at a greater velocity. However, this relationship is, of course, more complex than this. For example, Penner et al. (29) established that the sum of ball speed was equal to both the mass of the club and ball and the coefficient of restitution between the ball and the clubhead (defined as the post-collision velocity and corresponding pre-collision velocities) (31). Thus, to achieve greater ball speed and shot distance, CHS has a significant influence; however, impact location on the clubface must also be considered (23,33,41). The impact between the clubface and ball must be central and in line with the center of gravity, occurring at what has been coined the clubface's 'sweet-point' or center of percussion (41). Sweeney et al. (35) also reported that when impact location was considered in addition to CHS, the variance in peak resultant ball speed rose from 75% to 82%. However, despite impact location contributing to shot distance, it is not well represented in empirical golf studies. Impact location is a combination of vertical and horizontal distance relative to the center of the clubface (measured in millimeters). The research explains a few differing outcomes when off-center impact occurs. For example, Penner et al. (29) and Cochran and Stobbs (11) explained that an off-center impact could cause the clubhead to rotate about its gravity, causing something known as the 'gear effect'. This effect contributes to the spin rate, which is a characteristic of the launch and consequently influences the overall shot distance. Figure 2 visually represents the ball's impact location and consequent spin (11).

*** Insert Figure 2 about here ***

Spin rate is a vital launch characteristic determining the shot's success relative to distance. It results from the rate of rotation of the golf ball immediately after it separates from the clubface. When backspin is created, a lift force develops that acts perpendicular to the ball flight (11,29), enabling greater distance. Lift force acts at 90° to the drag force produced by the spinning ball and helps to counteract the gravitational pull of the ball's mass (11). Thus, a higher spin rate is necessary to produce a greater lift force (26).

In contrast, excessive spin rate and lift force can cause the ball to elevate too high, reducing shot distance (40). Wallace et al. (40) previously theorized that ball speeds must be high to achieve longer drives but also with concurrent ‘low’ spin rates. Specifically, spin rates between 2280 and 2640 rpm for tee shots have been suggested for an optimal lift to optimize drive distance (40). This suggestion indicates that an optimal range in spin rate exists to maximize carry distance. At the same time, any values on either side of the lower or upper boundary are likely to result in reductions in overall carry distance of the ball. Of note, average spin rates of 2,685 and 2,682 rpm have been recorded for PGA Tour and LPGA Tour players, respectively (13). Finally, clubhead impact factors have also been associated with spin rate. For example, when CHS, vertical impact location, and dynamic loft of the club were considered together, they could account for 55% of the variance in spin rate (12). However, no significant associations were present between horizontal impact location and spin rate.

Finally, to maximize shot distance, the angle of the ball at take-off relative to the ground must also be considered. This launch characteristic is expressed as 'launch angle' and provides another important determinant of shot distance. Wallace et al. (40) suggested that the optimal launch angle should be between 10 and 14° in elite golfers when using a driver off the tee. However, other research has indicated that launch angles as high as 20° may lead to maximal distance with a driver (11). It should be noted that these prior studies refer to maximal carry distance (i.e., the distance the ball travels through the air before landing). Still, when considering total distance, the additional roll of the ball must also be considered. The condition of the fairway is also likely to affect the ball's total distance, with greater rolling distances typically achieved when the ground is hard and dry. To achieve these theoretical launch angles of 10-20°, a golfer would be required to exhibit an extensive positive attack angle (i.e., hitting up on the ball) in conjunction with the right amount of dynamic loft (39). Notably, if dynamic loft increases too much, it will increase backspin and potentially negatively affect overall distance (11). However, like all of the factors and characteristics presented thus far, a combination of metrics results in optimal shot performance (25). For example, the TrackMan University website, which provides analytical data on optimizing shot performance, has reported that the optimal launch angle and spin for a golfer with a CHS of 95 mph and attack angle of 4° should be 15.6° and 2404 rpm, respectively, if aiming to maximize shot distance (37).

In contrast, optimal launch angle and spin for a golfer with a CHS of 95 mph and attack angle of -4° are reported as 11.4° and 3150 rpm, respectively (37). Thus, launch angle is influenced by the angle of attack, dynamic loft, and the impact location (35). Considering launch angle's influence on distance, several golfing articles have focused on the relevance of dynamic loft (3,34,35). Sweeney et al. (35) highlighted positive correlations between launch angle and dynamic loft ($r = 0.74$).

Partly supporting these findings, Betzler et al. (3) reported that launch angle was dependent on dynamic loft ($\beta = 0.58$) combined with the vertical impact location ($\beta = 0.61$). Finally, associations have also been established between ball speeds and launch angles. Wallace et al. (40) investigated the relationship between driver length and ball launch conditions among nine golfers considered 'skilled' (although specific skill level or handicap was not reported). Findings displayed a significant negative relationship between ball velocity and launch angle ($F = 45.09$; $p < 0.001$ [r value not reported]), indicating that higher ball speeds may be associated with lower launch angles. Of note, though, this study did not directly measure distance, so it is impossible to fully determine the link between reduced launch angles and the outcome of shot distance.

In summary, the available literature identifies some key links between launch characteristics and impact factors: 1) the largest variance in ball speed can be accounted for by CHS, but this increases when impact location is also considered 2) launch angle is strongly influenced by dynamic loft, and 3) spin rate may have an optimal range (as opposed to constantly chasing lager values) and is strongly influenced by a combination of CHS, vertical impact location, angle of attack, and dynamic loft. It is worth acknowledging that when multiple impact factors are responsible for the overall distance of a shot, a theoretical optimum value for all can be calculated (37). However, the likelihood of this being achieved shot after shot is slim. Furthermore, the concurrent interaction between multiple metrics likely precludes any perfect association between any single metric and the overall distance the ball travels. Figure 3 provides a summary schematic of the metrics associated with shot distance.

** *Insert Figure 3 about here* **

Shot Dispersion

A blend of distance and accuracy off the tee is associated with lower golf scores (21). Dispersion is a measure of lateral accuracy of the golf shot and results from the ball's initial direction and spin axis (27) and is typically measured relative to a given target. For a right-handed golfer, a shot that deviates away from the desired target to the left would be considered a ‘pull’, while a shot to the right, a ‘push’. The upcoming section will review the current literature to highlight the primary impact factors and launch characteristics that influence shot dispersion.

Spin axis is a launch characteristic that influences shot dispersion and can be defined as the tilt of the axis around which the ball spins post-impact (25). Crucially, the spin axis will impact the side spin applied to the ball, which is a component of total spin about the vertical axis. To better understand the role of the spin axis, we must discuss the D-Plane Theory (22). Jorgenson (22) produced a theoretical assessment of the impact phase of the golf swing. The theory represents a relationship between two vectors: the normal vector relative to the clubface and the direction the clubhead is moving at impact. A plane is formed from these two vectors, with the ball flight lying on this plane. When using the D-Plane and measuring where the clubface points, a line is drawn along the ground perpendicular to the clubface (Figure 4.1), known as the "normal" to the clubface. Side spin can be explained by the tilted D-Plane, which results from the face angle being positioned right or left relative to the club path (Figure 4.2). These can be called ‘open face’ and ‘closed face’ angles. When considering a right-handed golfer, an open face angle describes the club face positioned to the right, whereas a closed face angle describes the club face positioned towards the left. Logically, left-to-right side spin will occur when a right-handed golfer orientates their face angle to the left. TrackMan has previously reported that for every 5° of spin axis tilt, the golf ball would disperse sideways by 3.5 yards per 100 yards of ball flight (37). Importantly, attempting to create side spin on the golf ball may be a desired shot outcome; however, the ability to intentionally achieve this is undoubtedly related to skill level.

In contrast, side spin can also be considered an error. Regardless of whether side spin is intentional, it will result in the ball curving, consequently causing dispersion of the golf shot. Hay (18) suggested spin axis is linked to the orientation of the clubface at impact and the path of the club face, which seems logical (i.e., if the clubface is not straight and, therefore, not pointed towards the target at ball impact, it stands to reason that the resultant shot would likely not be hit straight). In support of this, Miura (27) reported that face angle alone could explain 82% of the variance in the side spin axis. In addition, although the club path did not show any meaningful significance on dispersion, it also occurs in the horizontal plane and likely has some influence on the spin axis.

*** Insert Figure 4.1 about here ***

*** Insert Figure 4.2 about here ***

The launch direction is the second launch characteristic associated with the dispersion of the golf shot. The launch direction is the angle at which the ball takes off relative to the ground. Like the spin axis, launch direction can be attributed to more than one kinematic variable of the clubhead at impact (3,35). For example, horizontal club path, face angle, and horizontal impact location influence launch direction (3,35). Specifically, Sweeney et al. (35) found that face angle reported 82% of the variance in launch direction when using a driver. The initial lateral direction is significant in the drive, where a small error in face angle can cause a large ball dispersion relative to the target. For example, it has been reported that a 280-m drive would land 10-m offline if mishit by a 2° margin in the launch direction (35).

Further, this study reported that a 120-m wedge shot mishit by the same 2° margin would land approximately 4-m offline. An additional study by Wood et al. (42) conducted a two-part experiment to understand better how a golf club's delivered face angle and club path influences the golf ball's initial direction. A total of 731 shots were analyzed using the driver, 745 shots with a 7-iron, and 99 shots with a wedge for part one. A repeatable swing test was investigated using a robot to produce impacts with various face angles for the second part of their experiment. Both experiments found that the launch direction fell closer to the face angle than the club path. It was reported that face angle could account for up to 61-83% of launch direction, where 100% describes a launch angle entirely toward the face angle. Due to the large volume of shots investigated alongside the large cohort of participants and the number of clubs tested, the results indicate the link between face angle and launch direction (42).

In summary, values representing the influence of spin axis and launch direction on shot dispersion have been identified from the literature. Both club path and face angle have been shown to influence spin axis, with face angle having the strongest influence on launch direction. Figure 5 provides a summary schematic of the metrics associated with shot dispersion.

*** Insert Figure 5 about here ***

Practical Applications: Considerations for Practitioners

Recently, commercially available launch monitor technologies for indoor and outdoor use have allowed practitioners and players to monitor these outcome measures, launch characteristics, and impact factors. Two of the most prominent launch monitors utilized in the golfing field are the TrackMan Pro IIIe (more recently updated to Trackman 4) and the Foresight GC2+HMT systems (more recently, the GCQuad). An advantage of these launch monitor systems is their immediate feedback of metrics, which can help provide a more detailed insight into how a shot achieves a given distance and accuracy. However, to the authors’ knowledge, only one study has aimed to establish the accuracy of these portable launch monitor systems: TrackMan Pro IIIe and Foresight GC2+HMT, by comparing them to a high-speed 4-camera system (24). A summary of the results for both launch monitors can be seen in Table 2. Collectively, it seems that these launch monitors are reasonably accurate relative to a high-speed camera system; however, the authors deduced that data pertaining to ball parameters may be more useful than those gathered from club parameters. In addition, it’s worth noting that these two launch monitor systems are placed in completely different positions when aiming to quantify shot outcomes. Specifically, Trackman is positioned 2-3 m behind the ball, whereas the Foresight system is perpendicular to the ball. Thus, it is likely that these different positions somewhat explain why the differences in error vary for both systems relative to a high-speed camera set-up.

*** Insert Table 2 about here ***

Despite the usefulness of knowing the launch monitors are largely accurate, no data appears to be available on their reliability. Previous literature has outlined the importance of establishing the reliability of any test protocols we undertake (6,38) as this initially provides confidence in undertaking further analysis, as well as enabling us to utilize the variability score (i.e., coefficient of variation [CV]) to establish whether changes are more or less than the error in the test (5). Table 3 provides an example of how practitioners can use the CV to create target scores for a few example metrics for which launch monitors provide data. As previously noted by TrackMan (37), some metrics require a set range to optimize the outcome of any given shot (e.g., spin rate); thus, not all metrics require a larger value to be optimized. Therefore, practitioners should likely only apply this 'target setting' for metrics where there is no doubt that the larger value benefits golfers (e.g., CHS, ball speed, and distance).

*** Insert Table 3 about here ***

In addition, although somewhat anecdotal, the usability of some of these metrics in our deterministic model (Figure 1) is likely dependent on a golfer's skill level. For example, assuming that a professional golfer can exhibit reasonably consistent scores for CHS and distance if asked to hit a shot with the same intended outcome is logical. In contrast, a golfer with a handicap of 18 may exhibit consistent data for CHS, but the ability to transfer that to consistent, maximal distance is likely questionable. This theory is supported by empirical research from Betzler et al. (3). They showed that as handicap decreased (i.e., indicative of more skillful players), golfers exhibited increased CHS and improved efficiency (i.e., the ratio of ball speed to CHS). Therefore, considering these findings, such a deterministic model or framework may evolve as a golfer's skill level improves. This further supports the notion of practitioners measuring the variability in test scores for all metrics if using launch monitor technologies, as the usability of some metrics may somewhat depend on the skill level of a golfer.

Finally, these findings have presented practitioners with an overview of how key golfing metrics are associated with and might impact the outcome of any given golf shot off the tee, with particular reference to distance and dispersion. Given the paucity of published data on some of these launch characteristics and impact factors, it is challenging to determine their relevance from a practical standpoint for S&C practitioners. However, given that the role of an S&C practitioner is one of support staff and our focus is on optimizing performance in the sport, knowing how these variables inter-link provides a much broader and more holistic understanding of the outcomes of a golf shot are achieved and overall golf performance. Conceptually, this can only be considered a positive thing for an S&C practitioner's professional development in golf. Thus, moving forward, we suggest that practitioners aim not only to begin monitoring these metrics but also to determine their association with key physical characteristics, such as strength and power, in the same way, that has been done for CHS (4,14).

Conclusion

This review provides practitioners with an understanding of some key factors (launch characteristics and impact factors) that link to the outcome measures of shot distance and dispersion for any given golf shot. Despite the complex interaction of multiple factors, monitoring both launch characteristics and impact factors will help practitioners understand how the outcome of a golf shot has been obtained. Consequently, this will enable a more detailed feedback process for the golfer, which may assist with understanding what should be actioned to obtain the most desirable outcome for any given shot. As the first port of call, though, S&C practitioners should aim to establish the reliability of these metrics to understand better which ones exhibit stability and which are likely to show much greater variability.

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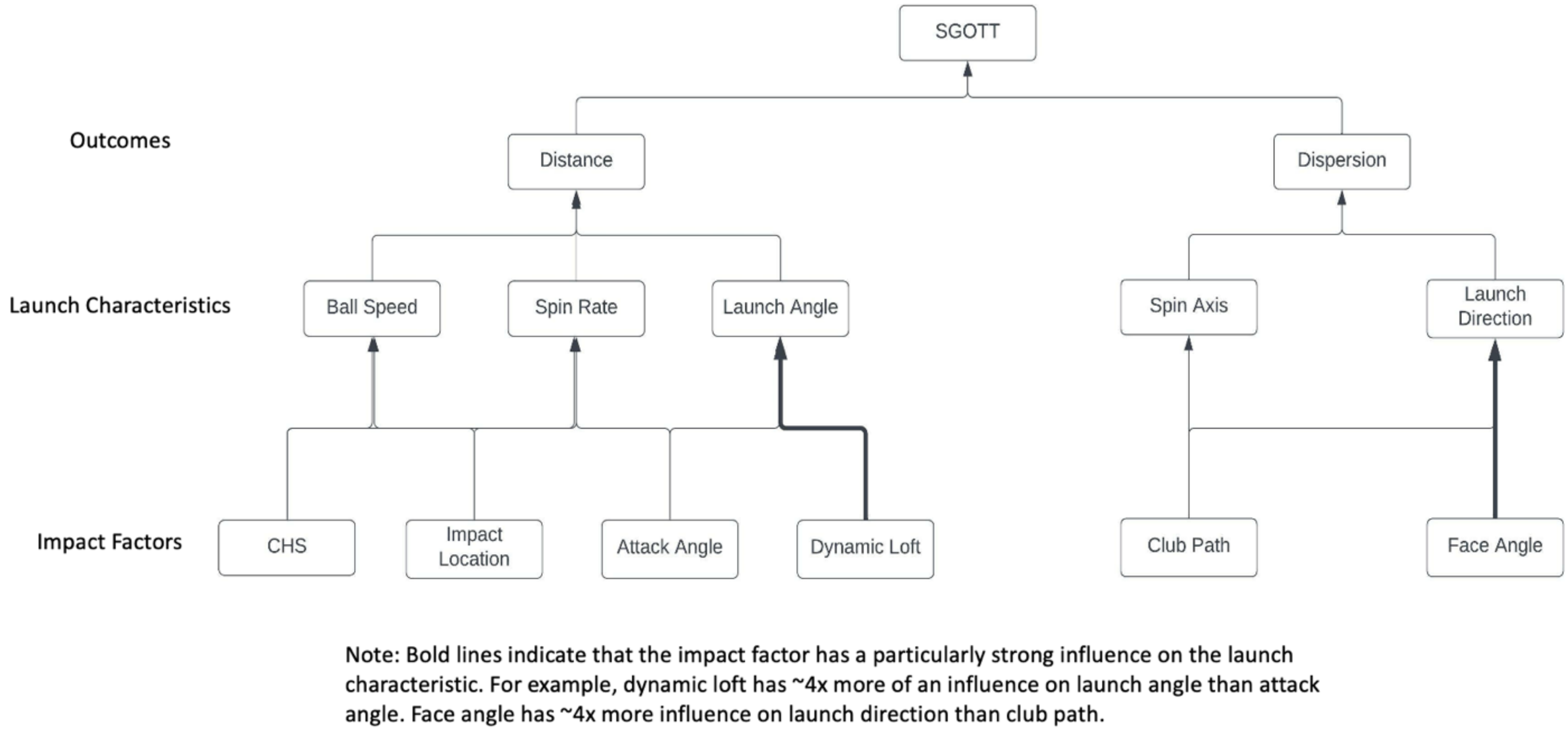

Figure 1. A proposed framework for monitoring golf performance measures that link to Strokes Gained off the Tee (SGOTT).

Table 1. Description of launch and impact parameters. All descriptions are taken from the Trackman website (40) and Leach et al. (36), with some adapted wording.

Parameter	Unit of Measurement	Description of Parameter
Launch Characteristics		
Ball speed	mph	The speed of the golf ball's centre of gravity immediately after separation from the club face
Spin rate	rpm	The rate of rotation of the golf ball around the resulting rotational axis of the golf ball immediately after the golf ball separates from the club face
Spin axis	°	The tilt angle relative to the horizon of the golf ball's resulting rotational axis immediately after separation from the club face (post impact).
Launch angle	°	The vertical angle relative to the horizon of the golf ball's centre of gravity movement immediately after leaving the club face
Launch direction	°	The horizontal angle relative to the target line of the golf ball's centre of gravity movement immediately after separation from the club face (post impact)
Impact Factors		
Clubhead speed	mph	The linear speed of the club head's geometric center just prior to first contact with the golf ball
Impact location	mm	The vertical and horizontal impact location distance relative to the center of face

Attack angle	°	The vertical direction of the club head's geometric centre movement at maximum compression of the golf ball
Dynamic loft	°	The vertical club face orientation at the centre-point of contact between the club face and golf ball at the time of maximum compression
Club path	°	The horizontal direction of the club head's geometric centre movement at the time of maximum compression
Face angle	°	The horizontal club face orientation at the centre-point of contact between club face and golf ball at the maximum compression of the golf ball

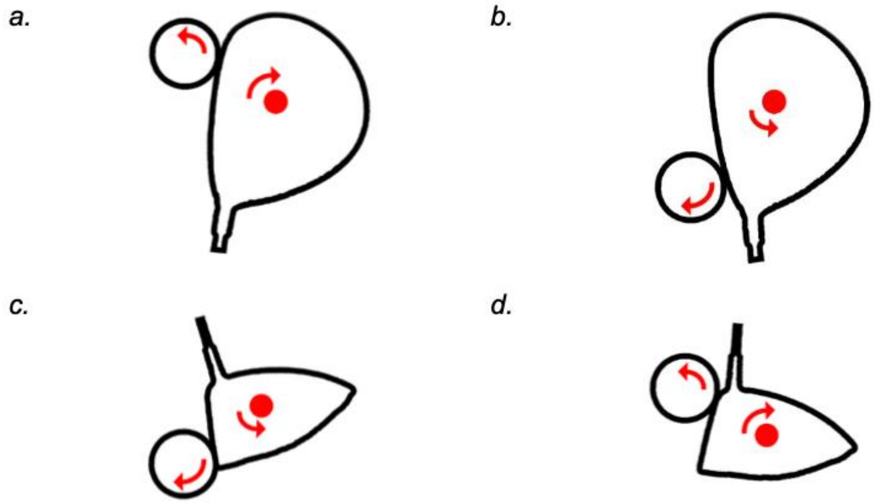

Figure 2. A visual representation of the 'gear effect'. Above view: a) toe impact and b) heel impact. Side-on view: c) low impact and d) high impact. The red dots represent the center of gravity in the clubhead, and the ball and clubhead arrows represent the body's rotational direction.

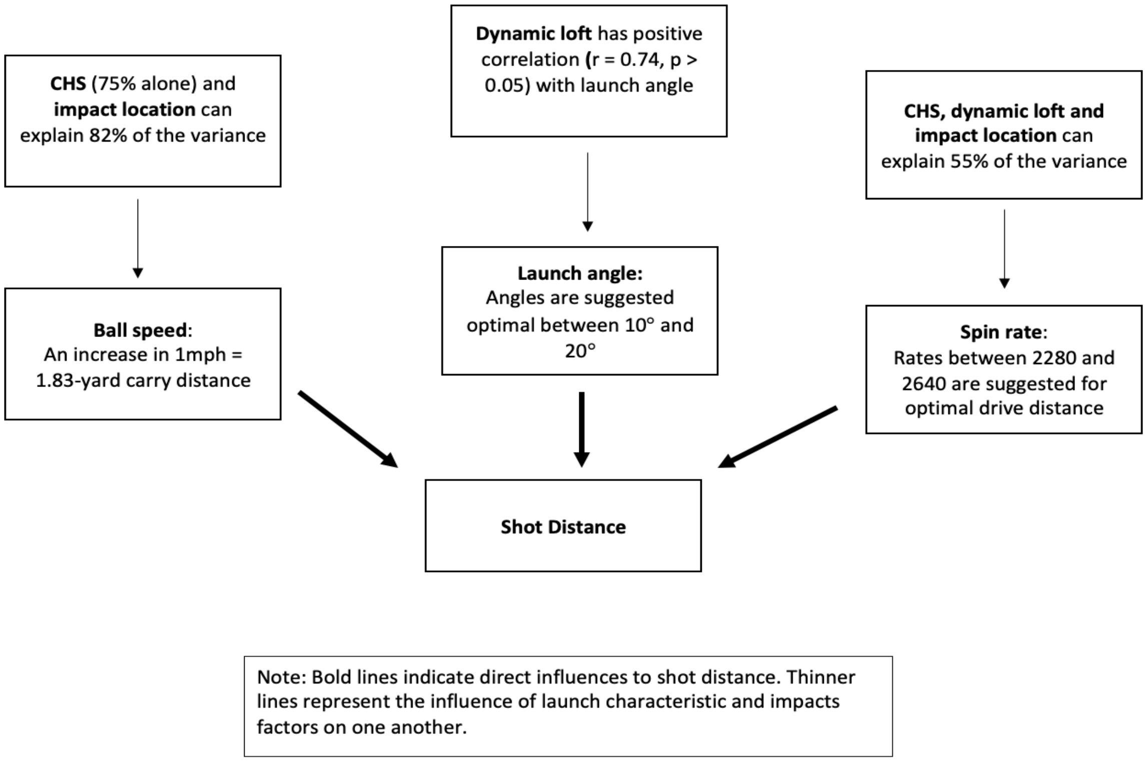

Figure 3. Display of metrics associated with shot distance.

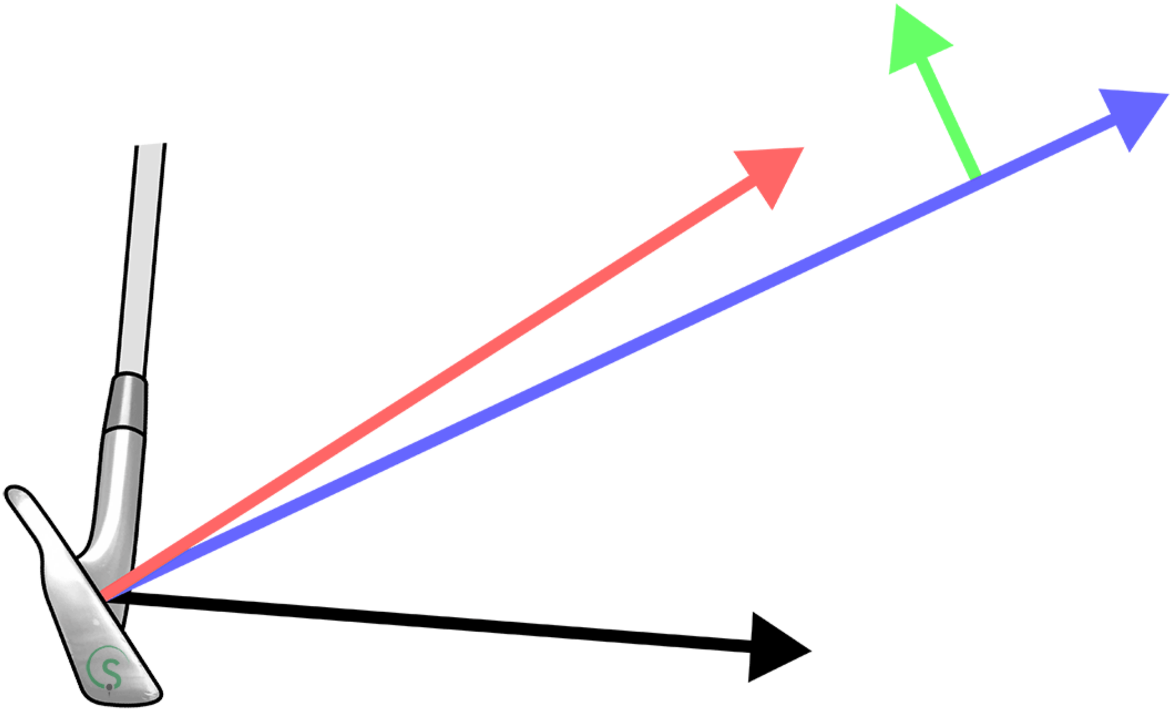

Figure 4.1 Based on the D-Plane theory (32) (Vertical plane). The blue line represents the ball's initial flight, which will be found on the two-dimensional space between the normal of the clubface and the clubhead's path through impact. The green line also represents the ball's flight but describes the direction of the lift on the ball. The black line represents the clubhead's direction (i.e., angle of attack). Finally, the red line represents normal to the clubface (i.e., dynamic loft).

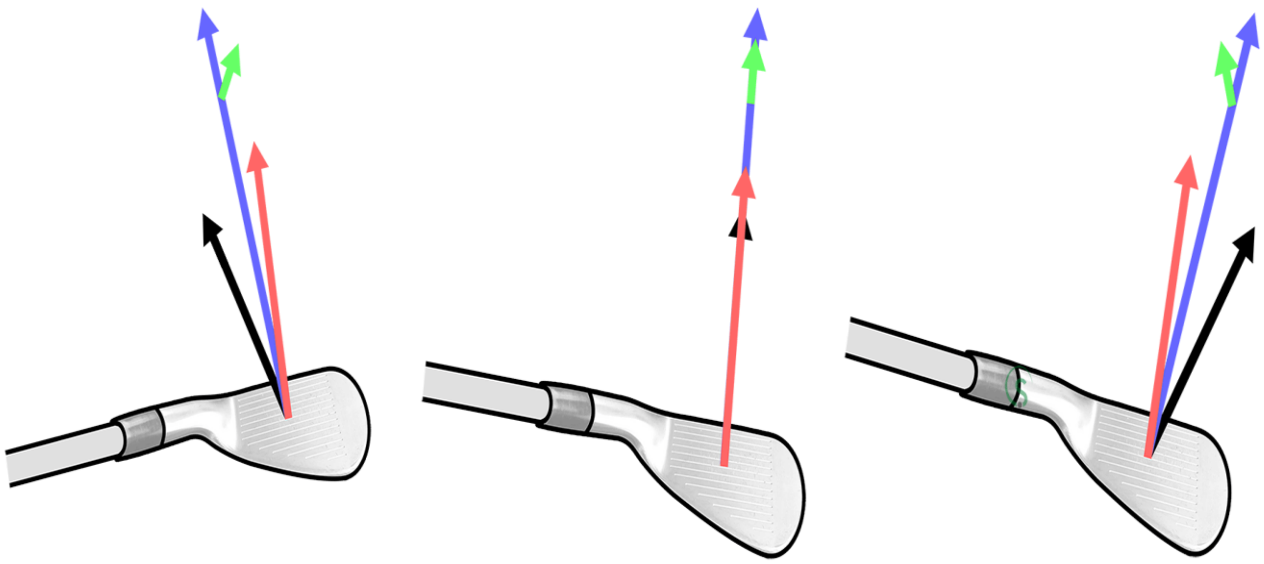

Figure 4.2 Based on the D-Plane theory (32) (Horizontal Plane). The coloured lines are represented the same as Figure 4.1. This figure represents the D-Plane tilt. The left figure shows the face angle to the left (open face angle) which results in left-to-right sidespin. The middle figure shows the normal to the clubface and the clubhead path both pointing in the same direction: towards the target. This means the direction of lift on the ball is straight upwards. The figure of the right shows the face angle to the right (closed face angle) which results in right-to-left sidespin.

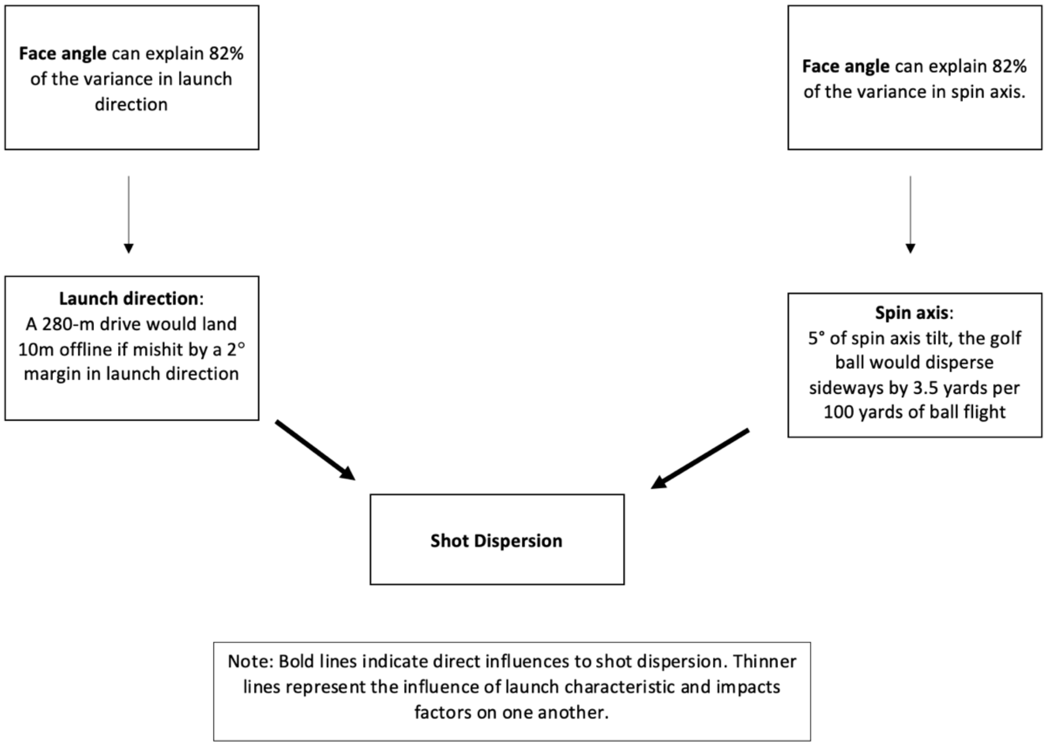

Figure 5. Display of metrics associated with shot dispersion.

Table 2. Mean data from the high-speed camera system and median differences for the Trackman Pro IIIe and the Foresight GC2+HMT launch monitor systems when using a driver (n = 8). *Note:* table adapted from the original publication by Leach et al. (7).

Golf Metric	**Camera System**	**Trackman Pro IIIe**	**Foresight GC2+HMT**
Ball velocity (mph)	146.2	0.2*	0.0
Launch angle (°)	11.2	0.0	0.3*
Launch direction (°)	2.3	0.0	-1.1*
Spin rate (rpm)	3140	-63*	-31
Clubhead velocity (mph)	100.8	-0.4*	3.9*
Attack angle (°)	3.9	-3.5*	-0.3
Club direction (°)	1.9	1.5*	0.1
Face angle (°)	2.1	-0.1	0.8*
Dynamic loft (°)	13.7	-0.5*	5.2*

** denotes significant difference against camera system ($p < 0.05$).*

mph = miles per hour; ° = degrees; rpm = revolutions per minute

Table 3. Hypothetical mean, SD and CV data, and target calculations to establish meaningful change when *n* = 1.

Golf Metric	Mean ± SD	CV (%)	Target Calculation	Target Score
Clubhead speed (mph)	112.6 ± 4.4	3.6	112.6 x 1.036	116.7
Ball speed (mph)	158.9 ± 6.1	5.2	158.9 x 1.052	167.2
Driving distance (yards)	276.8 ± 14.8	12.2	276.8 x 1.122	310.6

SD = standard deviation; CV = coefficient of variation; mph = miles per hour; rpm = revolutions per minute