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Effect of clubhead inertial properties and driver face geometry on golf ball trajectories

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Abstract

There are many factors that influence the amount of side-spin imparted to a golf ball during impact with a driver. In general, the best golf drives are launched with minimal side-spin, producing a straight ball trajectory with maximum carry distance. During off-centre impacts, side-spin is generated due to a phenomenon known as the "gear effect." The extent of the gear effect depends on clubhead design parameters such as the moment of inertia and centre of gravity location. The bulge of a driver is a design feature implemented to counter-act the side-spin produced by the gear effect. In this investigation, an impulse-momentum impact model and an aerodynamic ball flight model are used to (i) examine the effect of the centre of gravity depth (distance from clubface) on ball trajectory during off-centre impacts, (ii) test the efficacy of movable weight technology, and (iii) optimize the bulge radius in relation to the clubhead's centre of gravity depth and moment of inertia. In the first study, it is qualitatively shown that side-spin increases linearly with increasing centre of gravity depth. In the second study, it is found that movable weights can have a significant effect on ball trajectory, especially at higher swing speeds. In the third study, a relationship between the bulge radius, centre of gravity depth, and moment of inertia is developed, and an equation for calculating the optimum bulge radius is fit to the simulation results.

Keywords: Golf; Simulation; Clubhead Design; Optimization

1. Introduction

Designing a driver clubhead is a balancing act involving several physical design parameters. The goal is to produce a clubhead that provides the greatest carry distance while maintaining a suitable level of forgiveness for a particular golfer. A forgiving driver is one that maintains a high level of performance when contact is made outside the "sweet spot," or away from the centre of the clubface (CoF). When it comes to forgiveness, two of the most discussed design parameters are the clubhead's moment of inertia about a vertical axis (MOI_y), and its centre of gravity (CG) location. However, the bulge radius also plays a crucial role in controlling the trajectory of off-centre impacts, and often goes overlooked in the discussion surrounding driver forgiveness. Using computer models to simulate golf drives, the effect of these clubhead parameters on ball trajectory can be analyzed.

Nomenclature			
CoF	centre of face	b	bulge radius
CG	centre of gravity	e	coefficient of restitution
CG_x	distance from the CoF to the CG along the 'x' axis	X	actual carry distance
MOI_y	moment of inertia about the vertical 'y' axis	M	weighted carry distance
ω	angular velocity	W	weighting parameter
R	horizontal distance from the CG to the contact point	Z	deviation
r	golf ball radius	Z_{max}	maximum acceptable deviation

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1.1. Moment of inertia, centre of gravity, and the gear effect

A clubhead's MOI_y refers to its resistance to rotation about its vertical axis. A higher MOI_y provides more forgiveness during off-centre impacts with the golf ball. The mechanism behind this increase in forgiveness is due to a phenomenon known as the "gear effect," illustrated in Fig. 1 [1]. When the clubhead strikes the ball near the toe, the impact generates a moment about the clubhead's CG, causing it to rotate clockwise (right-handed golfer). During the impact, the clubhead and ball can be thought of as two gears that are meshed together. When two gears are meshed, the contact point on both gears must share the same tangential velocity, $v_{contact}$, equal to the radius of the gear multiplied by its angular velocity. Following this analogy, the side-spin imparted on the ball due to the gear effect can be approximated by Eq. (1), where R is the horizontal distance from the clubhead CG to the contact point (equivalent to CG_x), r is the radius of the golf ball, and ω is the angular speed, or spin.

$$R\omega_{club} = r\omega_{ball} \qquad (1)$$

Given that r is a constant, the side-spin resulting from the gear effect is proportional to $R\omega_{club}$. Increasing the MOI_y of the clubhead reduces ω_{club} during off-centre impacts, thus reducing the amount of spin imparted to the ball, which leads to longer and straighter drives. Conversely, increasing R by moving the CG away from the clubface increases the spin imparted to the ball. In Fig. 1, the counter-clockwise ball spin generated from a toe impact causes the ball to curl to the left [2]. This ball flight is known as a "draw." A heel impact causes the ball to spin in the opposite direction, and creates a ball flight that moves to the right, known as a "fade." Due to the forgiving nature of high MOI_y, the sport's governing bodies have limited the clubhead's MOI_y to a value of $5,900 \pm 100$ g-cm^2 [3].
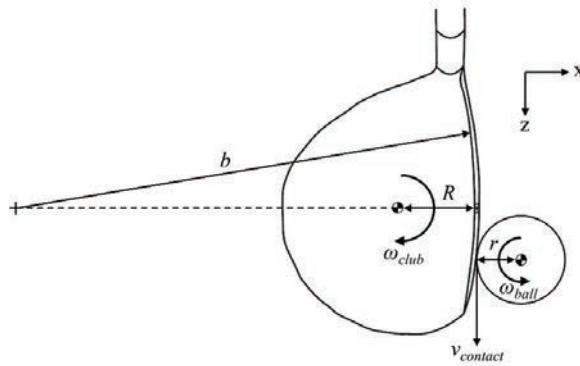
Fig. 1. Illustrating the gear effect for a toe impact.

1.2. Bulge

The bulge b of the clubhead is the radius of curvature of the clubface in the horizontal plane. The purpose of the bulge is to counter-act the side-spin generated by the gear effect during off-centre impacts. The bulge negates the gear effect both directly and indirectly. The bulge indirectly counter-acts the gear effect by altering the normal direction of the impact thus changing the direction of the ball's initial velocity. For example, the trajectory of a toed ball would start towards the right because of the bulge, and draw back towards the centre of the fairway due to the side-spin generated by the gear effect. The bulge directly counter-acts the gear effect spin by generating an opposing moment on the ball caused by the horizontal contact angle, assuming that the clubhead velocity is parallel to the X axis in Fig.1; this is analogous to the backspin produced by club loft. If the bulge radius is too small, the counter-spin generated can overpower the gear effect, causing the ball trajectory to remain straight or even curl the opposite way. If the bulge radius is too large, the spin generated from the gear effect will be overpowering, causing the ball to curl too much. Selecting the correct bulge radius can be the difference between a driver that is forgiving and one that is not.

1.3. Golf Drive Simulation

To simulate golf drives with varying clubhead parameters, an impulse-momentum impact model validated with finite-element analysis [4] is used in conjunction with an aerodynamic ball flight model [5]. The impact model requires the clubhead's physical properties and impact conditions as inputs, and outputs the ball launch conditions. The aerodynamic ball flight model uses the ball launch conditions to simulate the ball flight. An example of a perfectly square impact having an angle of attack of 0 degrees, an impact location of 2.5 cm towards the toe, and a clubhead speed of 50 m/s is shown in Fig. 2. Table 1 lists the nominal clubhead parameters used in the impact model. Due to the impact location being towards the toe, a drawing ball flight is observed.
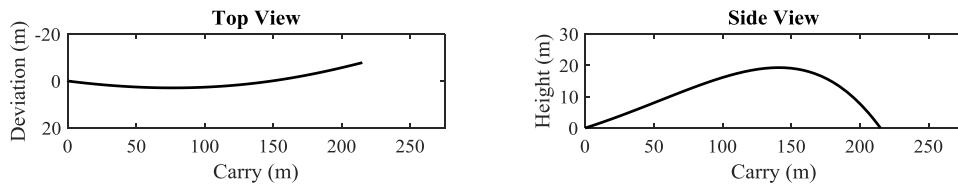
Fig. 2. Golf drive simulation.

Table 1. Nominal clubhead parameters.

Parameter	Value	Units	Parameter	Value	Units
Loft	10	deg	CG_z	0.0	cm
Lie	60	deg	Mass	200	g
Bulge	40	cm	MOI_x	3000	$g\text{-}cm^2$
Roll	35	cm	MOI_y	4500	$g\text{-}cm^2$
CG_x (R)	3.5	cm	MOI_z	2000	$g\text{-}cm^2$
CG_y	0.4	cm	e	0.83	-

2. Results

To demonstrate how different clubhead parameters influence the side-spin imparted to the golf ball, three studies were conducted using the drive simulation model. The first study is a variation of the CG depth (*R* or equivalently, CG_x) from front to back. The second study explores the effectiveness of today's movable weight technology by shifting the CG laterally (CG_z) from heel to toe. The third study involves an optimization and determines an optimum bulge radius for a given CG_x and MOI_y. Unless otherwise stated, the clubhead parameters used in these studies are the same as those listed in Table 1, and the impact is assumed to be perfectly square with a clubhead velocity of 50 m/s, and an angle of attack of 0 degrees.

2.1. Study 1: CG Depth

In this study, CG_x was varied from 2.8 cm to 4.2 cm in increments of 1 mm while holding all other clubhead parameters constant. The model was used to simulate drives with an impact location of 2.5 cm towards the toe. The change in ball trajectory due to the variation in CG_x is visible in Fig. 3. As predicted by the approximation of Eq. (1), the side-spin imparted to the golf ball increases with increasing CG_x, causing the ball to curl more with each increment. Fig. 4 shows that for this clubhead and impact location, the ball's side-spin increases with CG_x approximately linearly at 4.2 rad/s per mm.
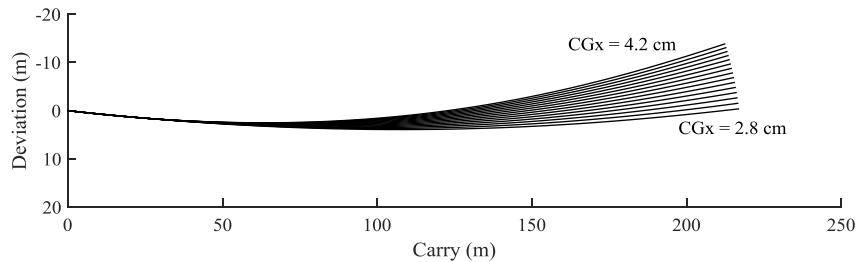
Fig. 3. Change in ball trajectory due to increasing CG depth.

2.2. Study 2: Movable Weights

One of the most popular and marketed advances in driver clubhead technology is the ability for the golfer to manually shift the CG location using external weights attached to the clubhead. TaylorMade claims that their latest driver, the M1, can create a 25 yard (22.9 m) draw to fade bias using a 15 g weight that slides on an embedded track from heel to toe [6]. This study uses the drive simulation model to assess the efficacy of movable weights.
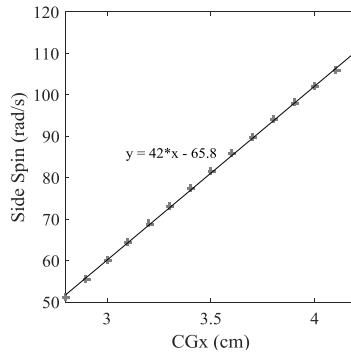
Fig. 4. Linear relationship between ω_{ball} and CG_x corresponding to Table 1 clubhead.

The slider track was estimated to have a displacement of 4 cm in each direction in the horizontal plane (i.e. a total heel-toe movement of 8 cm). For simplicity, it is assumed that the vertical displacement of the movable weight due to the curvature of the track has a negligible effect on the CG height (CG_y). Performing a centre of mass calculation with the movable weight positioned at the limits of the slider track leads to a 6 mm heel-toe CG_z translation. The two ball trajectories resulting from the lateral shift in CG location are shown in Fig. 5. These trajectories are the result of CoF impacts, and the deviation range is 15.1 m. There are a number of variables that could create a greater deviation range. For example, if the CG_x is moved back to 4.2 cm, and the MOI_y is reduced to 3300 g-cm^2, the simulated deviation range increases to 22.9 m. Furthermore, the deviation range depends greatly on clubhead speed, as shown in Fig. 6.
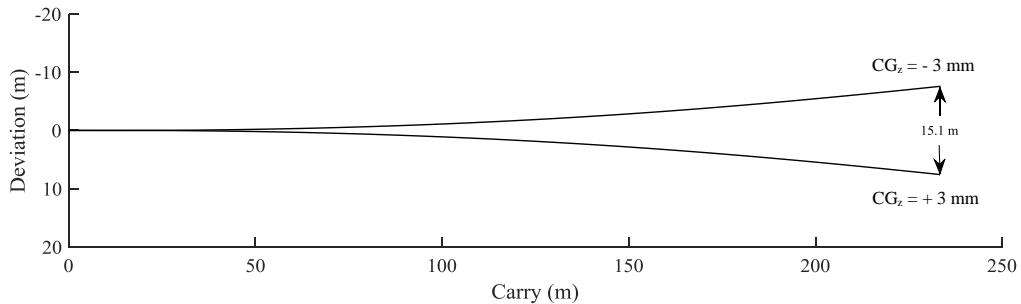
Fig. 5 Deviation range due to movable weight positioning.
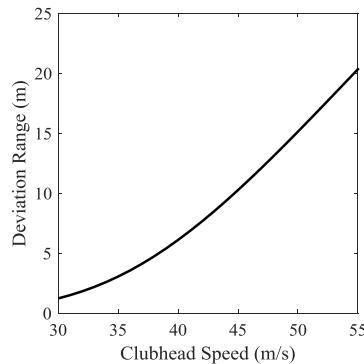
Fig. 6. Change in deviation range due to clubhead speed.

2.3. Study 3: Bulge Optimization

To observe the variance in ball trajectory due to off-centre impacts, the impact location was varied from -5 cm (heel) to 5 cm (toe) at intervals of 1 cm for a clubhead having a bulge radius of 30 cm. The impact location range was chosen based on the dimensions of a typical driver clubface and reflects the limits of successful driver impacts. The two plots in Fig. 7 illustrate the change in ball trajectory caused by off-centre impacts. It is observed that, in general, the impact furthest away from the CoF yields the poorest result, and each increment closer to the CoF is an improvement on the last. We assume that optimizing the bulge radius for the worst case impact location provides the best results for all impact locations for this particular clubhead.
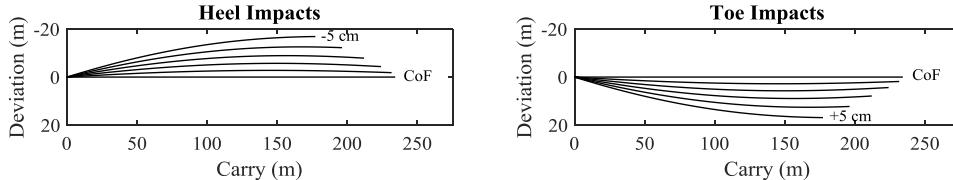
Fig. 7. Change in ball trajectory due to varying impact location.

The bulge optimization is performed using MATLAB's pattern search function, where the objective function is a weighted carry value calculated from the total carry and deviation from the centre of the fairway [1]. The objective function is designed to allow for a small amount of lateral deviation without a significant penalty to simulate the ball landing in the fairway, but larger deviations are heavily penalized to simulate landing in the rough or out of bounds. The objective function to be maximized is

$$M = X - We^{Z^2/Z_{max}^2} \qquad (2)$$

where X is the downrange carry, Z is the lateral deviation, Z_{max} is the maximum acceptable deviation, W is a weighting term, and e is the exponential function, not to be confused with the coefficient of restitution. For this application, W was set to 0.5 and Z_{max} was set to 5 m, creating a function that penalizes drives landing outside a 10 m wide fairway. For the set of clubhead parameters in Table 1, the optimum bulge was found to be 36 cm and the optimized ball trajectories are plotted in Fig. 8. However, the presented optimum bulge is only suitable for the set of clubhead parameters given in Table 1 and the objective function in Eq. (2). To develop a more general relationship, it is necessary to examine the change in optimum bulge with respect to MOI_y and CG_x.
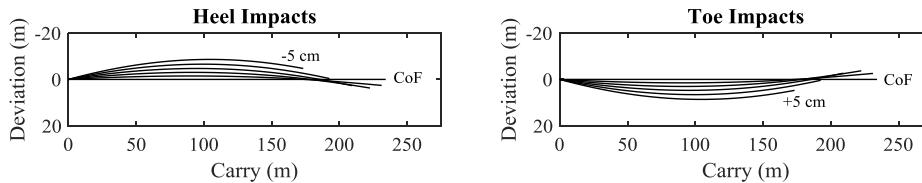

Fig. 8. Ball trajectories with optimized bulge radius.

The optimum bulge was found and plotted for different values of MOI_y and CG_x. The MOI_y was varied from 3000 to 6000 g-cm^2 at increments of 100 g-cm^2, and the CG_x was varied from 2.8 to 4.2 cm at increments of 1 mm. The results are presented as a surface plot in Fig. 9. Using a second order regression between CG_x increments, and a linear regression between MOI_y increments, Eq. (3) provides a surface fit to the optimum bulge results with less than 1% error from the values in Fig. 9.

$$b = \frac{(0.489MOI_y + 54.1)CG_x^2 - (4.98MOI_y + 652)CG_x + 16.9MOI_y + 13300}{1000} \qquad (3)$$
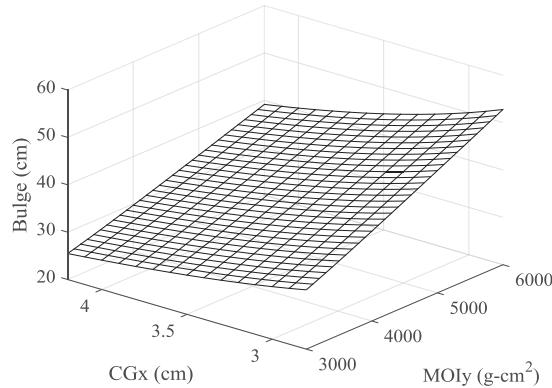
Fig. 9. Surface plot of optimum bulge for given CG_x and MOI_y.

3. Conclusions

Through the three studies conducted using the drive simulation model, it is evident that the CG position has a significant influence on ball trajectory. The first study demonstrated that for a particular clubhead, the golf ball's side-spin increases linearly with increasing CG_x, as predicted by Eq. (1) which approximates the gear effect. However, the magnitude of spin increase is subject to a number of other clubhead parameters and therefore can only be quantified on a case-by-case basis. The second study demonstrated that movable weight technology has merit with regards to generating a draw or fade bias. It should be noted, however, that the deviation of the altered ball trajectory is fundamentally dependent on swing speed. The third study developed a relationship between the primary clubhead parameters influencing horizontal ball trajectory, namely the bulge radius, the CG_x, and the MOI_y. Performing a bulge radius optimization in combination with a regression analysis has led to the formulation of an equation for calculating the optimum bulge radius given specific values of MOI_y and CG_x. By providing key insights into the effect of clubhead properties on ball trajectory, the three studies exemplify the benefits of using a computational drive simulation model for the purpose of clubhead design.

Acknowledgements

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