Sports Eng (2010) 12:69–75
DOI 10.1007/s12283-010-0034-3

ORIGINAL ARTICLE

Understanding the mechanisms of shaft deflection in the golf swing

Sasho James MacKenzie · Eric J. Sprigings

Abstract An understanding of shaft dynamics during the golf swing was gained through a series of theoretical simulations, using a 3D forward dynamics model. By resolving the resultant force applied at the grip end of the club into a tangential and a radial (centripetal) component, the mechanisms of shaft deflection were quantified. It was determined that radial force plays an important role in producing the toe-down and lead-deflections recorded in all golf swings made with a driver. However, the simulations also revealed that the recoil of the shaft, from its previously toe-up and lag deflected position during the downswing (due to tangential forces), plays at least an equally important role in determining the position and orientation of the clubhead at impact. It was further demonstrated that, due to the influence of the radial force component, maximum kick velocity is reached after the clubhead has passed beyond the neutral shaft position.

Keywords Golf · Shaft flexibility · Computer simulation · Optimization · Three-dimensional · Forward dynamics · Centripetal force

1 Introduction

The role of shaft flexibility in the golf swing was thoroughly examined in the previous papers in this series [1, 2]. Our optimized simulations revealed that kick velocity peaked after the clubhead had passed a neutral shaft position. This seems to be in contradiction to previous belief. According to Butler and Winfield [3], kick velocity is greatest when the shaft is straight at impact because the kinetic energy is maximized. This statement is in agreement with the characteristics of an oscillating spring system and is supported by other researchers [4]. To resolve this apparent contradiction, further research into the kinetics of shaft deflection was required.

The purpose of this paper was to gain a further understanding of the mechanisms behind the deflection of the golf shaft during the downswing. Specifically, the separate effects of both the tangential and radial force applied, by the golfer, to the grip end of the club were investigated. The role of these forces was examined through the use of mathematical modelling and simulation techniques.

2 Methods

Before the methodology of this research is explained, a conceptual framework for investigating the mechanisms of clubhead deflection is presented to assist the reader. From a Newtonian perspective, the forces applied to the club by the golfer, along with gravity, cause the shaft to bend during the downswing. A clearer understanding of the source of shaft bending can be gained by resolving the resultant force, applied at the grip end of the club, into a tangential component and a radial component. The tangential component acts in a plane formed by the X and Y axes, while the radial component acts along the Z-axis (Fig. 1).

Consider a simplified model of a golf club where a tangential force component acts perpendicularly to the

---

S. J. MacKenzie (✉)
Department of Human Kinetics, St. Francis Xavier University, 5000, Antigonish, NS B2G 2W5, Canada
e-mail: smackenz@stfx.ca

E. J. Sprigings
College of Kinesiology, University of Saskatchewan, Saskatchewan, Canada

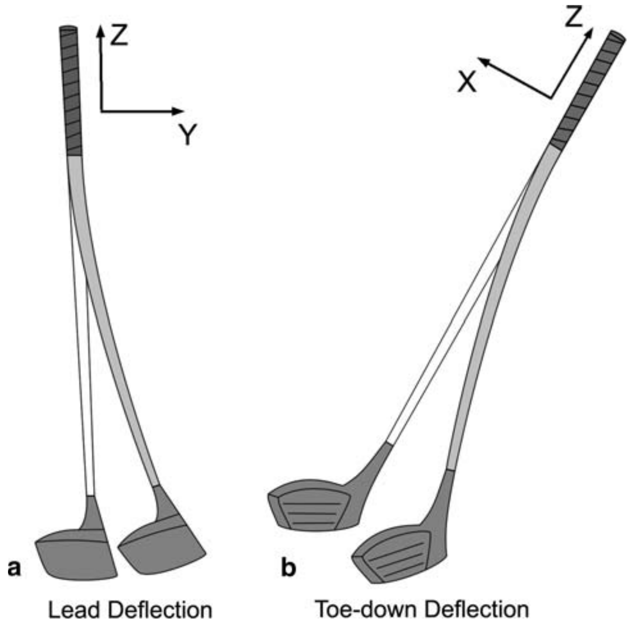

Fig. 1 The modelled shafts were capable of deflecting about two axes. **a** Deflection along the *Y*-axis represents lead/lag motion. **b** Deflection along the *X*-axis represents toe-up/toe-down motion

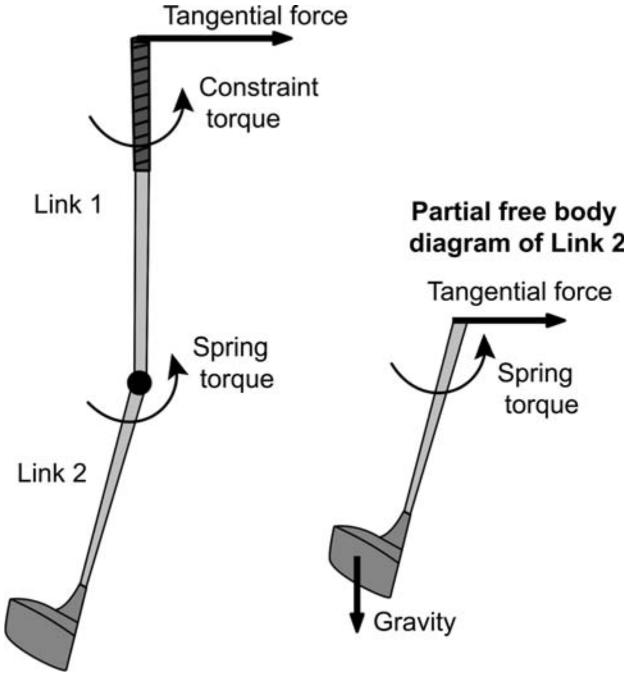

Fig. 2 Demonstration of the effect of tangential force on shaft bending

shaft at the grip end of the club. Two uniform rigid links are connected by a revolute joint that is spanned by a rotational spring-damper element (Fig. 2). A tangential force is applied by the golfer at the top of Link 1 to accelerate the club laterally, while a stabilizing constraint torque is also applied by the golfer at the top of Link 1 to prevent Link 1 from rotating. As a result, the top of Link 2 will also experience a positive, although slightly reduced, tangential force. This force at the top of Link 2 will result in torque acting about the center of mass of Link 2 which will tend to rotate the link clockwise. The rotation of Link 2 will stretch the rotational spring-damper until an equilibrium position is reached with Link 2 lagging behind Link 1.

Through friction from the golfer's hands, radial force is also applied along the longitudinal axis of the shaft to maintain the club's circular path during the downswing. Because of the offset position of the center of mass of the clubhead relative to the line of action of the radial force, this radial force will cause the shaft to bend. To visualize this, consider that a radial force is applied at the top of Link 1 during the swing, while a compensating constraint torque is also applied at the top of Link 1 to prevent its rotation (Fig. 3). As a result, the top of Link 2 will also experience a positive, although slightly reduced, vertical force. This force at the top of Link 2 will produce a torque about the offset center of mass of Link 2, which will tend to rotate the link counter-clockwise. The nature of this bending will tend to pull the clubhead into a leading and toe-down position as impact approaches.

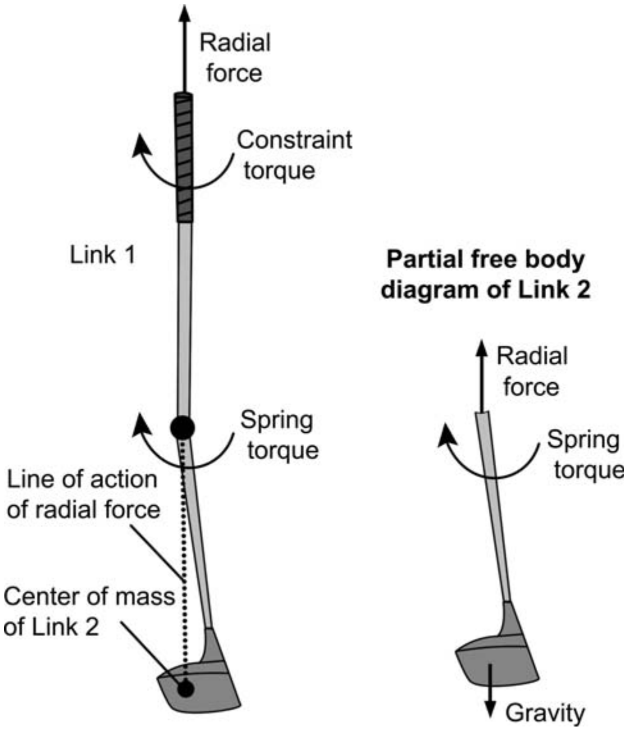

Fig. 3 Demonstration of the effect of radial force on shaft bending

2.1 Model description

A representative mathematical model of a golfer was constructed using a six-segment (torso, arm, and four club segments), 3D, linked system (Fig. 4). The golfer portion of the model had four degrees of freedom. The model was capable of the four fundamental motions in the downswing: torso rotation, horizontal abduction at the shoulder, external rotation at the shoulder, and ulnar deviation at the wrist. Four muscular torque generators which adhered to the force–velocity and activation rate properties of human muscle were incorporated to add energy to the system. The four segments of the modelled club were connected in series by rotational spring-damper elements (Fig. 4) [5]. The shaft segments were capable of deflecting about two axes (Fig. 1).

The model's goal was to maximize horizontal clubhead speed at impact with the golf ball. An optimization scheme was employed, which used a single activation muscle control strategy where the timing of each muscular torque generator was controlled separately. The optimization search engine was developed by the author and employed an evolutionary algorithm approach, as generally expressed in theory by Michalewicz [6]. Further details on model development, parameters, and optimization can be found in the first paper of this series [1].

2.2 Repositioning of the clubhead center of mass

Several authors [4, 7, 8] have stated that the shaft is deflected in the lead and toe-down directions at impact because of the radial force acting on the center of mass of the clubhead, which is offset from the axis of the shaft. If the radial force is the dominating factor controlling shaft deflection at impact, then reversing the position of the clubhead's center of mass should reverse the direction of shaft bending. For example, if the center of mass is geometrically moved into a position in front of (positive *Y* direction) the longitudinal axis of the shaft (Fig. 5), then theoretically, the shaft should be deflected in the lag direction at impact.

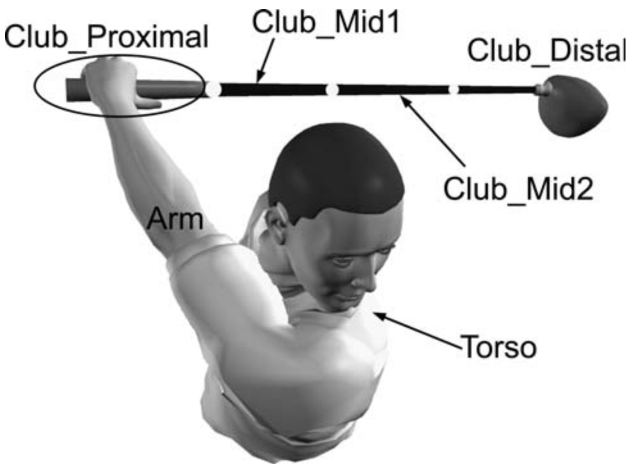

Fig. 4 The initial configuration for the 3D, six-segment model used to simulate the downswing. Note that the most proximal club segment was comprised both the golfer's hand and grip of the club

To help understand the influence of radial force on clubhead deflection, a series of simulations were conducted that systematically manipulated the position of the clubhead center of mass. Clubhead deflections were compared for three positions of the center of mass along both the toe-up/toe-down and lead/lag axes: in-line, normal and reversed (Fig. 5). In-line refers to the center of mass being collinear with the longitudinal axis of the shaft. Normal refers to the position of the center of mass in a typical driver. Reversed refers to the placement of the center of mass in the exact opposite location along a particular axis. For example, with the 'normal' position, the center of mass of *Club_Distal* (the most distal club segment) is located 4.7 cm in the negative *Y* direction (Fig. 5). Therefore, the reversed condition would be to place the center of mass at 4.7 cm in the positive *Y* direction relative to the axis of the shaft. For each condition, the position of the center of mass of *Club_Distal* was only changed along either the *X*- or the *Y*-axis, and not both simultaneously. A baseline measure of clubhead deflection was established by generating an optimized simulation with the normal clubhead center of

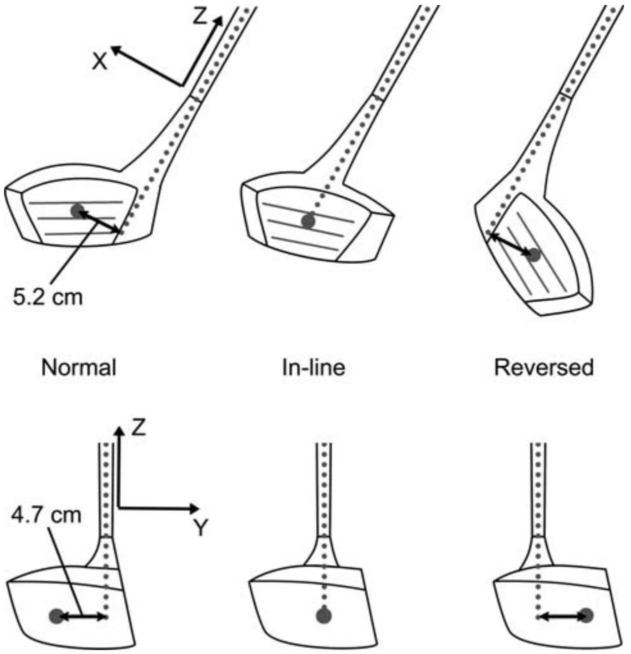

Fig. 5 These six images represent possible club designs, which would result in changes to the position of the center of mass as described in Sect. 2.2. The *top-row* demonstrates repositioning the center of mass along the *X*-axis, which would primarily affect toe-up/down deflection (see Fig. 6). The *bottom-row* demonstrates repositioning the center of mass along the *Y* axis, which would primarily affect lead/lag deflection (see Fig. 7). The reversed condition in the *top-row* is analogous to hitting a ball off the face of a left-handed driver while using a right-handed swing

mass position first. This also permitted the identical golf swing (in terms of the 'golfer' portion of the model) to be used for each condition. This condition is referred to as the normal optimized swing in Table 1.

2.3 Removal and isolation of radial force

Manipulating the position of the clubhead's center of mass was expected to foster an understanding of the influence of radial force on shaft bending. However, even if the center of mass is geometrically placed in-line with the shaft at the start of the simulation, the shaft can still bend due to tangential forces. This would result in the clubhead center of mass no longer being collinear, and radial force would once again exert its influence. Therefore, a second methodology was implemented which allowed both the complete removal and complete isolation of radial force.

An optimized simulation of the downswing was generated with the model. The forces and torques applied to the club by the golfer portion of the model were recorded every 10^{-4} s. The force and torque vectors were each broken down into three components based on the relative reference frame attached to the grip end of the club (Fig. 1). A second confirmatory simulation was conducted with just the four-segment club model, in which the six force and torque measures taken at each time step in the previous simulation served as input. As would be expected, the resulting clubhead speed and clubhead deflection measurements were identical to the first simulation. A third simulation was performed in which the values for the radial force at each time step were set to 0 N, but the other force and torque measures remained the same. This allowed the effect of radial force to be removed from the golf swing. A fourth simulation was performed in which only the values for radial force were input at each time step, and all other force and torque measures were set equal to zero. This allowed the effect of radial force to be isolated during the downswing.

3 Results

3.1 Repositioning the clubhead center of mass

During the first half of the downswing (0–0.15 s) tangential forces, not radial, exerted the greatest influence on the toe-up/toe-down deflections. This can be reasoned because all three conditions (normal, in-line, and reversed) showed very similar deflection patterns and all had peak toe-up deflections of similar magnitude (~10 cm) during the first half of the downswing (Fig. 6; Table 1). However, as impact approached, radial force became an important factor in determining shaft deflection in the toe-up/toe-down direction. As expected by theory, the normal center of mass position condition resulted in a toe-down deflection (−2.26 cm) at impact. The in-line condition approached zero, but finished with a small toe-up deflection (0.69 cm) at impact. Reversing the center of mass position along the *X*-axis resulted in a toe-up deflection (3.60 cm) at impact (Table 1).

The small influence that radial force had on lead/lag deflection is evident during the first half of the downswing (0–0.15 s) (Fig. 7). In the normal condition, the effect was to pull the center of mass in-line with the shaft which resulted in the clubhead moving into a slightly leading position (~1 cm). Reversing the position of the center of mass had an equal and opposite effect, as the clubhead was pulled into a lagging position. The in-line condition served as a verification of the radial force influence; when the center of mass was collinear with the shaft, no bending in the lead/lag direction occurred during the first half of the downswing. However, radial force during the last half of the downswing had a clear influence on lead/lag deflection

Table 1 Clubhead deflections for all simulated downswing conditions

Simulation condition	Peak lag (cm)	Lead/lag at impact (cm)	Peak toe-up (cm)	Toe-up/down at impact (cm)
Normal optimized swing	−3.62	6.25	10.20	−2.26
C of M *Y*-axis				
In-line	−5.96 (−2.34)	3.97 (−2.28)	10.20 (0.00)	−2.30 (−0.04)
Reversed	−8.47 (−4.85)	1.21 (−5.04)	10.22 (0.02)	−2.31 (−0.05)
C of M *X*-axis				
In-line	−3.61 (0.01)	6.69 (0.44)	10.71 (0.51)	0.69 (2.95)
Reversed	−3.66 (−0.05)	6.70 (0.45)	11.29 (1.09)	3.60 (5.86)
Radial force removed	−4.87 (−1.25)	4.72 (−1.53)	10.67 (0.47)	−1.02 (1.24)
Only radial force acting	0.00 (3.62)	1.22 (−5.03)	0.00 (−10.20)	−1.33 (0.93)

Values in parenthesis show the difference from the normal optimized swing

C of M center of mass

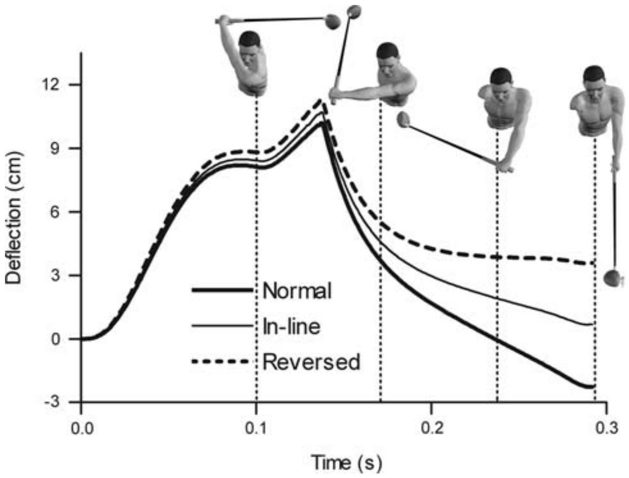

Fig. 6 Toe-up/toe-down deflections for three different clubhead center of mass positions. *Normal* refers to a standard driver that has the center of mass located in the toe-up direction relative to the projection of the shaft. *In-line* refers to having the center of mass collinear with the shaft. *Reversed* refers to having the center of mass in the toe-down direction relative to the projection of the shaft

at impact. The normal condition showed the greatest lead deflection at impact (6.25 cm) followed by the in-line condition (3.97 cm) and then by the reversed condition (1.21 cm) (Fig. 7; Table 1).

3.2 Removal and isolation of radial force

Complete removal of the radial force component from the optimized swing of the golfer model had a simple effect on clubhead deflection in both the lead/lag and toe-up/toe-down directions (Fig. 8). The pattern of deflection remained very similar when radial force was removed. Only the magnitude of deflection was affected, and the difference in magnitude between the conditions increased as impact approached. This was logical considering that radial force increased as impact approached (radial force peaked at 456 N approximately 0.01 s before impact). Lead deflection at impact remained positive (4.72 cm) but was reduced from its value under normal conditions (6.25 cm) (Table 1). Toe-down deflection at impact remained negative (−1.02 cm) but was also reduced in magnitude in comparison to the normal condition (−2.26 cm) (Table 1). This reduction seems reasonable when the effect of radial force on shaft deflection was isolated (Fig. 9).

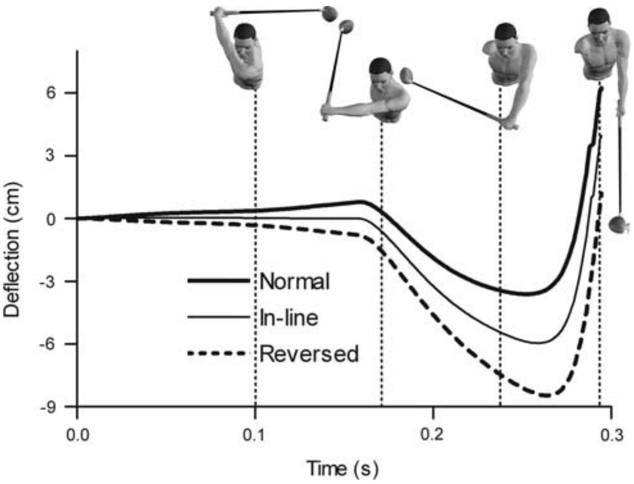

Fig. 7 Lead/lag deflections for three different clubhead center of mass positions. *Normal* refers to a standard driver that has the center of mass located in the lag direction relative to the projection of the shaft. *In-line* refers to having the center of mass collinear with the shaft. *Reversed* refers to having the center of mass in the lead direction relative to the projection of the shaft

When acting in isolation, radial force produced nearly identical patterns of clubhead deflection about both axes of clubhead deflection (Fig. 9). Because of the offset position of the clubhead's center of mass, the shaft was gradually pulled into its maximum leading position (1.22 cm) at impact. Similarly, the shaft was gradually pulled into its maximum toe-down position (−1.33 cm) at impact when radial force acted as the lone contributor to shaft deflection (Table 1). The club showed more deflection in the toe-down direction than in the lead direction because the clubhead center of mass was more offset along the *X*-axis (5.2 cm) than the *Y*-axis (4.7 cm) (Fig. 5).

4 Discussion

In the second paper of this series [2], it was shown that kick velocity peaked (7 m/s) while the clubhead was near its maximum leading position (6.25 cm). This was in contradiction to existing theory, which suggests that kick velocity should be maximized when the shaft is straight at impact

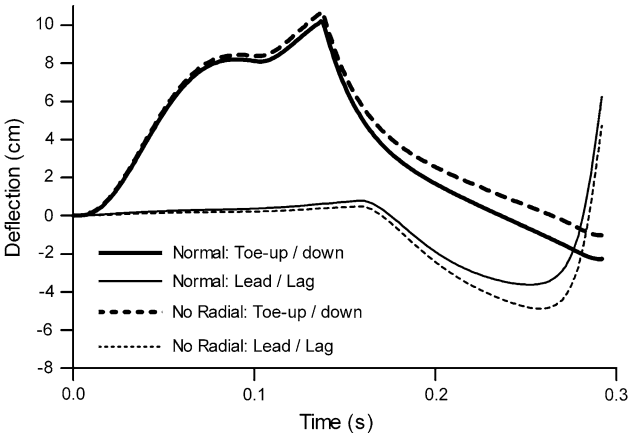

Fig. 8 Comparison of shaft deflections between the normal optimized swing, and the same swing with radial force removed

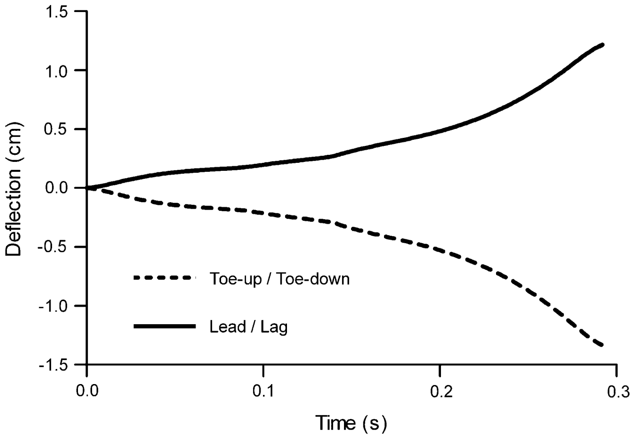

Fig. 9 Shaft deflection when radial force acted in isolation of all other forces and torques supplied by the simulated golfer to the club during the normal optimized swing

[3]. However, based on the results from this study, an explanation is readily available. The influence of a large radial force (456 N), acting on the offset position of the clubhead center of mass, will continue to increase kick velocity past the neutral shaft position. This finding highlights the potential benefits of using optimized forward dynamic simulations. Simultaneously collecting shaft deflection and clubhead velocity data with the required precision would make it difficult to measure this phenomenon experimentally.

The largest magnitude of clubhead deflection was in the toe-up direction and occurred during the early phase of the downswing. Tangential forces acting along the *X*-axis were the primary cause of these deflections. Initial bending in the toe-up direction may superficially appear to be storing energy which could later be released to increase clubhead speed. However, due to the 90° rotation of the club about the lead arm during the final stage of the downswing, the energy stored in the initial part of the downswing will not be returned to the clubhead along the intended direction of ball flight. Further, any residual effect of this deflection present at impact only has a small effect on the dynamic loft of the club. Based on the results of this study, it is our position that the initial toe-up deflection only serves to increase the variability in a golf swing. This information supports the view of those golf instructors that advocate a ‘smooth’ transition into the downswing, as opposed to a highly accelerated (i.e. rushed) transition that would lead to larger shaft deflections early in the downswing.

The next important period of shaft deflection occurred in the lag direction over the final half (after 0.15 s) of the downswing. The maximum lag deflections were approximately 4 cm in magnitude. Tangential forces, acting along the *Y*-axis, were the primary cause of deflections in the lag direction. Shaft deflection in this direction resulted in the storage of strain energy that had the potential to be released near impact and result in a faster clubhead speed. This period of shaft deflection cannot be predicted from a 2D model and is essentially why a 3D simulation was needed to sufficiently model the downswing.

The final phase of shaft deflection was the most important since it explained clubhead orientation at impact. Over the final few hundredths of a second of the downswing, the clubhead rapidly moved from its maximum lagging position into its maximum leading position at impact. The lead deflections at impact for the normal optimized simulation were approximately 6.25 cm in magnitude. The complete removal of radial force during the downswing only reduced lead deflection to 4.72 cm (Fig. 8; Table 1). Therefore, when acting in isolation, the tangential forces that occur during the late phase (after 0.15 s) of the downswing were a major contributor to the lead deflection at impact. The complete isolation of radial force demonstrated that, while acting alone, radial force only resulted in 1.22 cm of lead deflection at impact (Fig. 9; Table 1).

Toe-down deflection at impact was a result of both radial and tangential force components over the final third of the downswing. Both radial and tangential force components contributed approximately equally to the magnitude of toe-down deflection at impact. When acting in isolation, radial force was shown to deflect the clubhead by −1.33 cm in the toe-down direction. For the optimized swing, toe-down deflection was −2.26 cm at impact; therefore, just over half of that deflection was the direct result of radial force action.

Several researchers claim that radial force is the dominant factor producing shaft deflection at impact [3, 4, 8–10]. The results from the current study demonstrated that when radial force acted in isolation, shaft deflection in either the toe-down or lead direction did not exceed 1.33 cm in magnitude. Yet, several authors [3, 4, 9] as well as the results from this study have reported that shaft deflection at impact can exceed 4 cm in both directions. At first glance, a possible explanation of these ambiguous findings is that the radial force generated by the model used in this paper may not have been large enough to produce the previously reported magnitudes of shaft deflection. However, the peak magnitude of radial force (456 N) measured during the optimized swing (45 m/s) was within the range presented in the literature. Williams [11] deduced that Bobby Jones generated a clubhead speed of approximately 50 m/s and applied a radial force of 476 N to his driver at impact. Vaughan [12] (360 N) and Neal and Wilson [13] (315 N) reported reduced values for peak radial force during the downswing. However, these researchers generated their results from 3D inverse dynamic analyses of live golfers which bring into question how much their smoothing techniques reduced peak values. Miura [14] predicted a radial force of 414 N from his 2D model which generated a clubhead speed of 46.8 m/s. Mather and Jowett [10] stated that radial force approaches 500 N for clubhead speeds of 45 m/s. Considering these reported results, it appears as though 456 N, as occurred in our simulation study, is a reasonable value of radial force.

In conclusion, radial force was found to be responsible for increasing the relative velocity of the clubhead with respect to the hands even after the shaft had passed a neutral (straight) position. In general, radial force plays an important role in facilitating the toe-down and lead deflections recorded in all golf swings made with a driver. However, the recoil of the shaft from its previously toe-up and lag deflected position (introduced by the tangential forces over the last third of the downswing during the time that the lead arm is rotated through ~90°) plays at least an equally important role in determining the position and orientation of the clubhead at impact.

Acknowledgments The authors acknowledge the Natural Sciences and Engineering Research Council of Canada for providing funding support.

Conflict of interest statement The authors declare that they have no conflict of interest.

References

1. MacKenzie SJ, Sprigings EJ (2009) A three-dimensional forward dynamics model of the golf swing. Sports Eng 11:165–175
2. MacKenzie SJ, Sprigings EJ (2009) Understanding the role of shaft stiffness in the golf swing. Sports Eng 12:13–19
3. Butler JH, Winfield DC (1994) The dynamic performance of the golf shaft during the downswing. In: Cochran AJ, Farrally MR (eds) Science and Golf II: Proceedings of the World Scientific Congress of Golf, 1st edn. E&FN Spon, London, pp 259–264
4. Horwood GP (1994) Golf shafts: a technical perspective. In: Cochran AJ, Farrally MR (eds) Science and Golf II: Proceedings of the World Scientific Congress of Golf, 1st edn. E&FN Spon, pp 247–258
5. Nesbit SM (2005) A three dimensional kinematic and kinetic study of the golf swing. J Sports Sci Med 4:499–519
6. Michalewicz Z (1996) Genetic algorithms + data structures = evolution programs. Springer, New York
7. Jorgensen TP (1994) The physics of golf. American Institute of Physics Press, New York
8. Milne RD, Davis JP (1992) The role of the shaft in the golf swing. J Biomech 25:975–983
9. Mather JSB, Cooper MAJ (1994) The attitude of the shaft during the swing of golfers of different ability. In: Cochran AJ, Farrally MR (eds) Science and Golf II: Proceedings of the World Scientific Congress of Golf, 1st edn edn. E&FN Spon, UK, pp 271–277
10. Mather JSB, Jowett S (1998) The effect of centrifugal stiffening on the bending stiffness of a golf shaft. In: Farrally MR, Cochran AJ (eds) Science and Golf III: Proceedings of the World Scientific Congress of Golf, 1st edn. Human Kinetics, UK, pp 515–521
11. Williams D (1967) The dynamics of the golf swing. Q J Mech Appl Math 20:247–264
12. Vaughan CL (1981) A three-dimensional analysis of the forces and torques applied by a golfer during the downswing. In: Morecki A, Fidelus K, Kedzior K, Wit A (eds) International Series of Biomechanics VII-B, 1st edn edn. University Park Press, Warsaw, pp 325–331
13. Neal RJ, Wilson BD (1985) 3D kinematics and kinetics of the golf swing. Int J Sports Biomech 1:221–232
14. Miura K (2001) Parametric acceleration: the effect of inward pull of the golf club at impact stage. Sports Eng 4:75–86