Proceedings

The Golf Shaft's Influence on Clubhead-Ball Impact Dynamics †

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Abstract: A long-held assumption in golf research is that the driver-ball impact is accurately modelled as a collision between two free bodies, i.e., the clubhead is not attached to the shaft. The purpose of this work was to examine the validity of this assumption using multibody simulation and motion capture technology. Ten elite golfers were recruited to participate in a motion capture experiment to validate a Rayleigh beam model of a flexible club. Using the six degree-of-freedom motion of the grip as an input to the model, the simulated shaft deflections showed good agreement with the experiment. An impact model based on volumetric contact was integrated with the flexible club model and was used to compare the launch conditions of free-body and full-club impacts. Analysis of the launch conditions revealed that the shaft creates a stiffening effect that resists clubhead rotation during contact, corresponding to an increase in ball speed and suppression of the gear-effect relative to free-body impacts. The results demonstrate that shaft dynamics cannot be treated as negligible when evaluating driver impact mechanics.

Keywords: golf; multibody simulation; impact modelling; shaft; motion capture

1. Introduction

The Search for the Perfect Swing, first published by Cochran and Stobbs in 1968, presents a compilation of scientific studies examining all areas of golf [1]. Their pioneering work is the first comprehensive scientific analysis of the sport. Regarding the collision between clubhead and ball, the scientists claimed the clubhead 'free-wheels' through impact, such that all the resistance to impact is borne by the inertia of the clubhead. In other words, the shaft nor player can influence the impact dynamics. The accompanying experiment involved using a two-wood with a hinge at the hosel; the point of connection between the clubhead and shaft. The hinge was designed to give way upon impact, allowing the clubhead to behave like a free-body. Compared to 30 shots with a normal-shafted club, the shots hit with the hinged club averaged 215 yards (197 m), 5 yards (4.57 m) less than the normal club. The scientists dismissed the loss of yardage, attributing it to a decrease in clubhead speed caused by the 'useless' weight of the hinge, or the wobbly feel of the club that may have caused the golfers to swing easier. Since this landmark study, a critical assumption in golf engineering is that the driver impact is accurately modeled as a free-body collision.

Countless studies have subsequently exploited the free-body assumption to provide insights on optimal clubhead design, using both finite-element (FE) and analytical models. In industry, free-body FE simulations are used extensively by golf equipment manufacturers to assess the performance and structural integrity of prototype clubhead designs. Consequently, the free-body assumption plays a pivotal role in golf engineering and research, but there is limited evidence supporting it. Tanaka et al. [2] offers the only study on the influence of the golf shaft, comparing experimentally validated FE impact simulations featuring a highly simplified club to those with the clubhead alone. Their full-club simulations showed an increase in ball speed at all impact locations and a suppression of the gear-effect [3] relative to the free-body simulations. Advances in multibody simulation and motion capture technology present a new opportunity to investigate the golf shaft's influence on clubhead-ball impact dynamics. This work extends the simple cylinder-pendulum club of Tanaka et al. to real golf clubs, leveraging the computational efficiency of symbolic models to simulate impacts resulting from a dynamically loaded shaft and realistic clubhead.

2. Experimental

2.1. Motion Capture

Ten elite male right-handed golfers (handicap ≤ 4.0) were recruited to participate in a golf swing motion capture experiment. An 8-camera passive optical system (Nexus, Vicon) was used, recording the motion of a driver fitted with reflective markers at 723 frames per second. Prior to the experiment, three important reference frames were calibrated: the global frame, the clubface frame, and the grip frame. The reference frames are depicted in Figure 1a. The global frame's *X* axis points directly at the target and the *Z* axis is perpendicular to the ground. The clubface frame is positioned at center-face (CF) with the X_C axis normal to the clubface and Y_C axis parallel with the grooves, directed towards the golfer. The grip frame is positioned on the shaft axis and is offset from the butt end of the club to coincide with the position of the golfer's hands. The Z_G axis is coincident with the shaft axis and points toward the butt end, while X_G lies in the XZ_C plane (during static calibration). Two additional video cameras were used to locate the golf ball. Smoothing algorithms were applied to the downswing and the club kinematics were extrapolated to the precise moment of impact. The impact location on the clubface was calculated using the golf ball's coordinates. The players hit 10 drives with the main criterion that they were satisfied with the quality of their shot, to provide consistency among their 10 swings. The launch conditions for each drive were recorded using a launch monitor (GC2, Foresight Sports) that measured ball speed, launch angle, azimuth, backspin and sidespin. Positive launch angle is measured about the -*Y* axis, and positive azimuth and side spin about the -*Z* axis. The driver used in the experiment had a nominal loft of 9.0 degrees and a 'stiff' rated shaft.

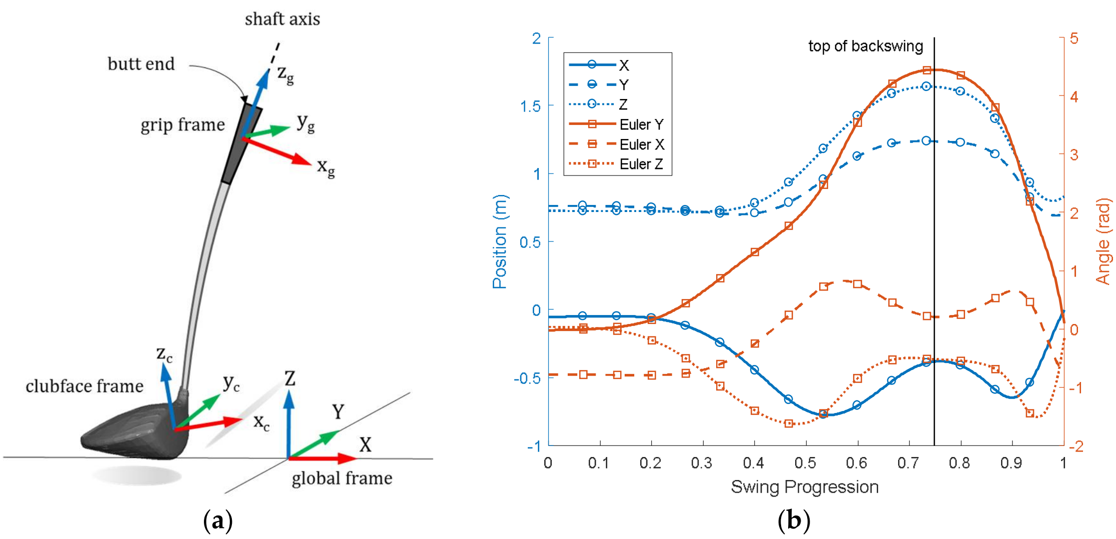

Figure 1. (**a**) Motion capture frames of reference; (**b**) 6-DOF grip motion for representative swing.

2.2. Club Properties

The clubhead mass, center of gravity (CG) location, and moment of inertia (MOI) about the vertical (crown-sole) axis and horizontal (heel-toe) axis were empirically determined. Clubhead mass and CG measurements were obtained using a digital balance (EJ-1500, A&D Weighting) and bespoke

CG fixture, while MOI measurements were obtained using the USGA standard method and equipment [4]. The remainder of the inertia matrix was populated using the clubhead solid model. All empirical measurements included the shaft sleeve, fastener, and motion capture markers.

The shaft's bending and torsional stiffness profiles were provided by the manufacturer. The profiles were generated from numerical models based on the construction of the golf shaft, where the stiffness was estimated from the number of layers of material in a particular region of the shaft. The outer diameter of the shaft was measured optically (LS-7030, Keyence, Osaka, Osaka Prefecture, Japan) and the wall thickness was measured using a magnetic thickness gauge (Magna-Mike 8500, Olympus, Hong Kong, China). The cross-sectional area was calculated using the inner and outer radii and third-order polynomials were fit to the material properties, providing continuous functions of the shaft's length from the butt end.

3. Modelling

3.1. Flexible Club & Swing Simulation

MapleSim's (Version 2016.2, Maplesoft) standard flexible beam component was used to model the deformation of the golf shaft in a full swing simulation. The symbolic formulation is based on Rayleigh beam theory and was implemented via the principle of orthogonality by Schmitke and McPhee [5]. The formulation was previously applied to model golf shaft deformation by Sandhu et al. [6], who compared simulation results of the flexible beam model to motion capture data. However, results were only given for the ten milliseconds leading up to impact, and reasonable agreement was reported only for droop and dynamic loft. In this work, the flexible club model is compared to motion capture data for 10 full swings from two golfers.

The six degree-of-freedom (6-DOF) motion at the grip is used to drive the golf swing simulation. The position data consists of the three translational (X, Y, Z) and rotational components (Y-X-Z Euler angles). The grip motion of a representative golf swing is plotted against the normalized progression of the swing in Figure 1b, where the swing begins at the address position and finishes at impact. The vertical line indicates the top of the backswing. To ensure continuous accelerations at the grip, cubic spline interpolation was applied between the position data points.

3.2. Flexible Club Validation

Using the computed bending stiffness provided by the manufacturer, the simulated shaft deflection was greater than in the experiment, but the model was able to reproduce the unique bending profiles of each golfer and the subtle patterns within them. Speculating that the simple numeric model provided by the manufacturer may have underestimated the actual stiffness of the shaft, the deflection error was minimized by scaling the bending stiffness by a factor of 1.5. The beam's internal damping parameters were determined in the same minimization, but did not affect the shaft deflection significantly. Using the scaled bending stiffness, the mean simulated droop and lead deflections for 10 swings of two golfers are compared to the experiment in Figure 2, where the shaded bands represent one standard deviation from the experimental means. The droop and lead deflection are measured as the relative displacement of the hosel in the Y_G and X_G directions, respectively. It should be noted that in the simulation, the grip position is held still for one second, allowing the shaft to reach static equilibrium through internal damping before the swing commences. The initial simulated droop resulting from static equilibrium under gravity is not observed in the experimental results as golfers typically rest the clubhead on the ground. The dynamic agreement between the flexible club model and motion capture experiment provides confidence when using the flexible club model to simulate impacts. The dynamic loading of the shaft at impact could significantly affect the shaft's influence on impact dynamics, and was not factored into the study of Tanaka et al. [2].

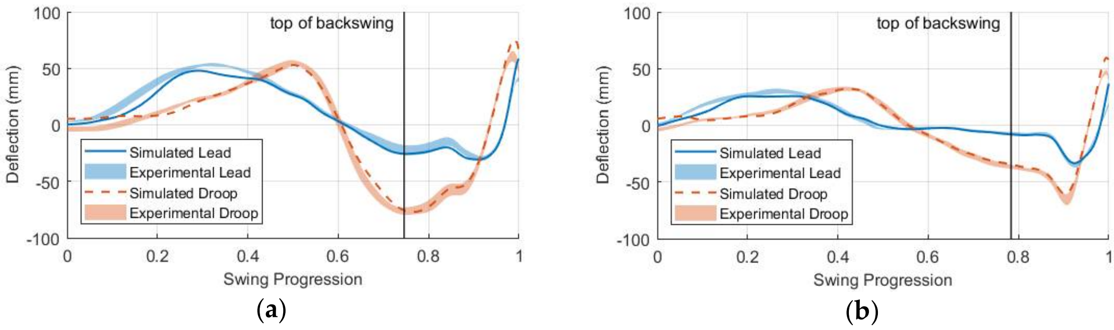

Figure 2. (**a**) Golfer A shaft deflections; (**b**) Golfer B shaft deflections.

3.3. Impact Model and Validation

An analytical impact model featuring a normal force based on volumetric contact [7], continuous velocity-based friction [8] and a tangentially compliant golf ball was tuned using experimental launch conditions and integrated with the flexible club in the MapleSim dynamic simulation. The parameters of the impact model were identified by minimizing the difference between the simulated and experimental ball speed and spin rate in full-club impact simulations. Due to the small deflection errors in Figure 2, the simulated clubhead deliveries in the full-swing simulations do not perfectly reflect the experimental clubhead deliveries and therefore cannot be associated with the experimental launch conditions. To correct for this, the flexible club model was initialized at the moment of impact using the experimental data. To drive the club through impact, the grip forces were estimated using inverse dynamics in the full-swing simulations. Similar methods for obtaining grip forces were used by Nesbit [9]. Figure 3 shows the simulated grip forces for Golfer A, provided in the grip reference frame. The shaded bands represent the standard deviation of the 10 swings. The grip forces were extrapolated for the 0.5 ms of impact and were used to drive the full-club impact simulations dynamically.

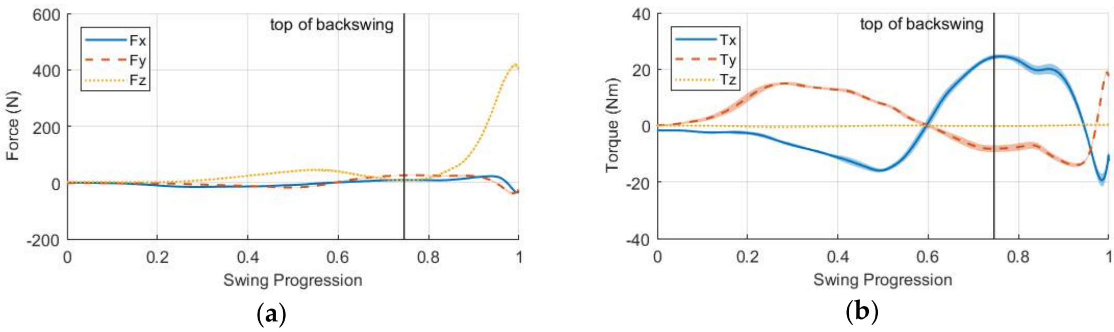

Figure 3. (**a**) Golfer A grip forces; (**b**) Golfer A grip torques. Provided in the grip reference frame.

The impact model does not account for the degradation of the coefficient of restitution (COR) across the clubface so only impacts within 12 mm of CF were used in the tuning process ($n = 60$) under the assumption that the COR is relatively constant within this area. A training dataset was formed by selecting 40 impacts at random and the model was tested against the remaining 20. The mean errors (*simulated – experimental*) for the simulated launch conditions are shown in Table 1.

Table 1. Simulated launch condition mean errors and standard deviations for training ($n = 40$) and test ($n = 20$) datasets.

Dataset	Ball Speed (km/h)	Launch Angle (deg)	Azimuth (deg)	Back Spin (rpm)	Side Spin (rpm)
Training	−0.24 ± 1.60	1.00 ± 0.33	0.16 ± 0.69	−59.4 ± 334	184 ± 286
Test	0.17 ± 1.96	0.93 ± 0.39	−0.15 ± 0.54	−150 ± 287	239 ± 269

The impact model shows good agreement for ball speed and azimuth, and reasonable agreement for launch angle and backspin. Relatively large errors are reported for sidespin, which may have been caused by imprecise calibration of the motion capture system and manually positioned launch monitor. A misalignment of just two degrees between the vertical axes of the global frame and the launch monitor could create 100 rpm of sidespin error. Regardless, free-body and full-club impacts will be compared using the same impact model, so the side spin error in Table 1 has little effect on the meaningfulness of the results when comparing the two impact scenarios.

4. Simulation Results, Discussion & Conclusions

The shaft was removed from the full-club impact simulations and the launch conditions of free-body impacts were compared to those using the full-club, ultimately revealing the influence of the golf shaft. For a representative clubhead delivery, the impact location was varied to cover a 75 by 37.5 mm area on the clubface and the launch conditions were recorded. Figure 4a,b show contour plots of the simulated ball speeds (in km/h) for full-club and free-body impacts, respectively. The dashed circle represents the area for which the impact model was tuned. Similar to Tanaka et al., the full-club ball speeds are greater across the clubface. In both cases, maximum ball speed is located slightly off-center towards the toe. After further investigation, these locations were found to correspond to minimum clubhead spin after impact, indicating that there may be an inverse correlation between clubhead rotation and ball speed.

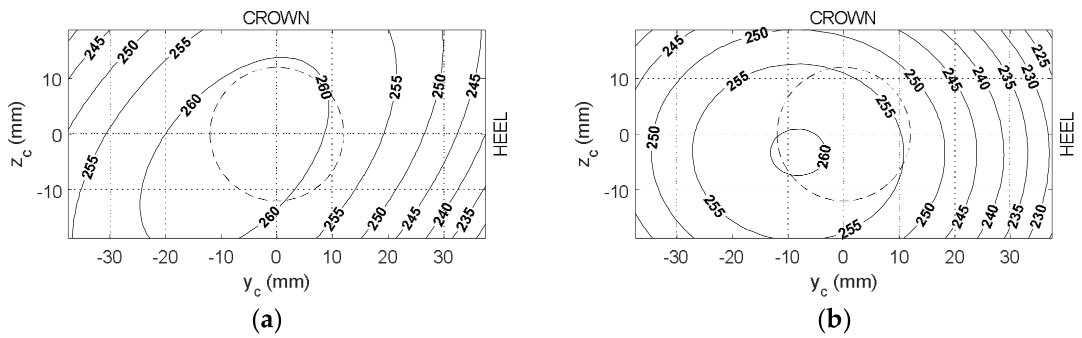

Figure 4. (**a**) Full-club ball speed (km/h); (**b**) Free-body ball speed (km/h).

Figure 5 displays contours of the *differences* (*full-club–free-body*) in ball speed, launch angle, azimuth, sidespin and backspin. The results in Figure 5 are fundamentally attributed to the reaction forces and torques generated at the hosel. The reaction creates a stiffening effect that helps maintain clubhead speed through impact and resists twisting of the clubhead. For off-center impacts, less energy is lost to the rotation of the clubhead and more energy is transferred to the ball. This effect is magnified in close proximity to the hosel, as shown by the increasing ball speed toward the high-heel area of the clubface in Figure 5a. The resistance to clubhead rotation also leads to a suppression of the gear-effect. Considering that positive side spin corresponds to fade spin, Figure 5d illustrates the suppression of the gear effect with the full-club's fade-bias towards the toe, and draw-bias towards the heel. The same phenomenon is responsible for differences in backspin in Figure 5e. Figure 5b and 5c show how the full-club resists the change in launch angle and azimuth caused by clubhead rotation. Overall, the results demonstrate the shaft's capacity to resist clubhead rotation during the contact period and alter the launch conditions, indicating that shaft dynamics cannot be treated as negligible when evaluating driver impact mechanics.

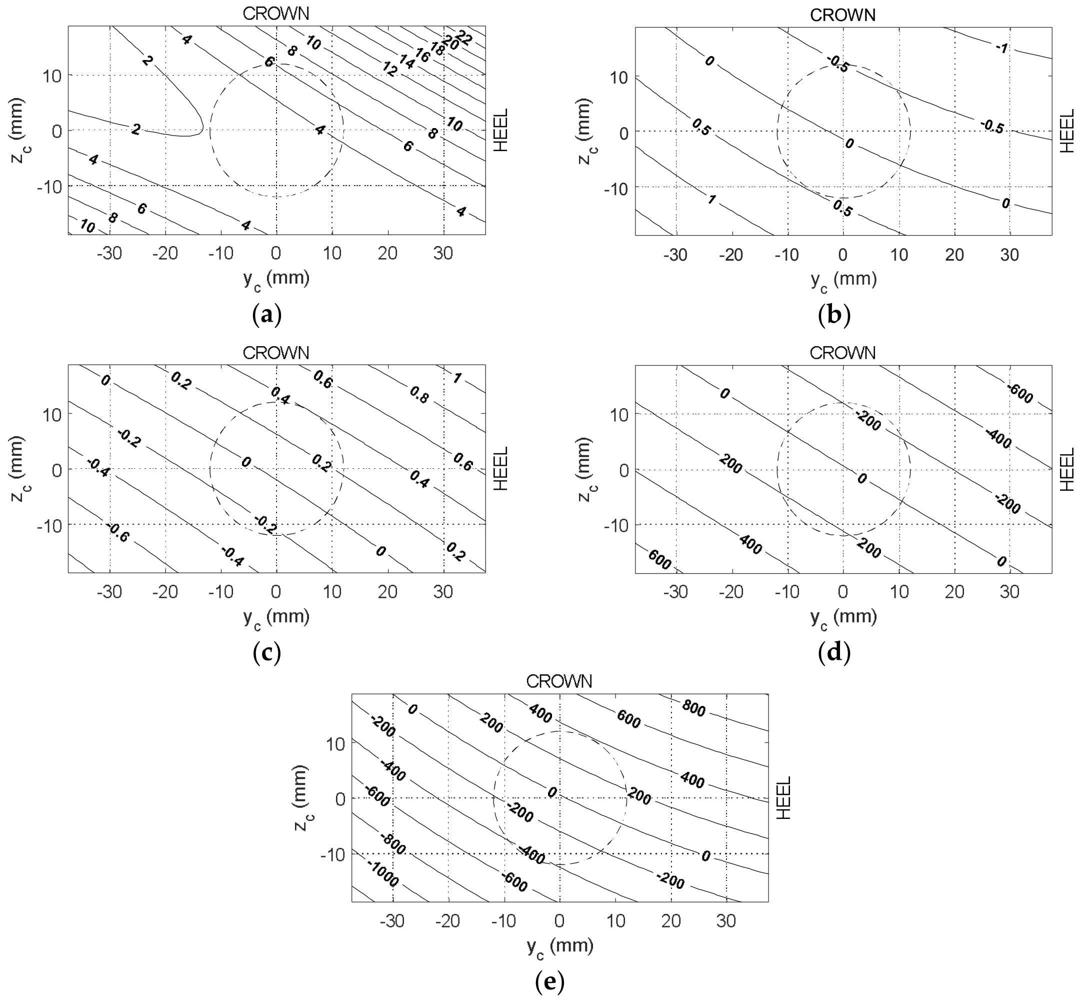

Figure 5. Launch condition differences across the clubface (*full-club–free-body*). (**a**) Ball speed (km/h); (**b**) Launch Angle (deg); (**c**) Azimuth (deg); (**d**) Side Spin (rpm); (**e**) Back Spin (rpm).

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Conflicts of Interest: The authors declare no conflict of interest.

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