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Predictive dynamic simulation of the golf swing, including golfer biomechanics and distributed flexibility in the shaft

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Abstract

A 3D predictive golfer model can be a valuable tool for investigating the golf swing and designing new clubs. A forward dynamic model for simulating golfer drives is presented, which includes a four degree of freedom golfer model and a flexible shaft model based on Rayleigh beam theory. Input torques for the golfer model are determined by an optimization process that maximizes clubhead speed while maintaining a square impact with the golf ball. Four flexible shafts with different bend profiles were simulated and the results suggest that, for a golfer with average swing speed, tuning the bend profile of the shaft can increase the clubhead speed at impact and the length of the golfer's drive.

Keywords: Golf swing model; Flexible shaft; Speed optimization; Shaft bend profile; Forward dynamic simulation

1. Introduction

Many attempts have been made to model the golf swing in the past 50 years. Kinematic models have been used to examine the motions of the golfer and can answer diagnostic questions like "What is the clubhead speed at impact?" (Vena, 2011) or "Is the golf swing really planar?" (Coleman, 2005). Inverse dynamic models take the diagnostic approach one step further and allow researchers to investigate the torques and forces required to swing the club (Nesbit, 2005). Finally, forward dynamic models of the swing allow for predictive simulations and the asking of 'what-if' questions like "What if the club's center of mass was shifted distally?" (Sprigings, 2001) or "What if the golfer was able to swing more powerfully?" (Sharp, 2009). Predictive forward dynamic models allow researchers and manufacturers to make design decisions in simulation rather than with expensive time-consuming experiments.

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The earliest forward dynamic golfer models were simple, planar double pendulums representing the golfer's left arm and club (Cochran & Stobbs, 1968). Lampsa(1975) used optimal control theory and a double pendulum model to predict maximum possible clubhead speeds. Sharp (2009) incorporated the torso as a separate body creating a planar triple pendulum model. A kinematic study by Coleman (2005) showed that a planar model is insufficient for studying the swing so MacKenzie (2009a) developed a 4 degree of freedom golfer model that incorporated two planes of rotation, one for the torso and one for the arms and club. This model was driven by joint torques that mimicked the activation characteristics of human muscles and was able to provide good agreement with experimental golf swings.

Manufacturers are now interested in varying flexibility ("bend profile") along the golf shaft, and its effect on the clubhead conditions at impact. MacKenzie's forward dynamic golfer model (2009b) included a flexible shaft that was modelled using four rigid segments connected by rotational spring dampers. Experiments were performed to find the correct parameters for the spring constants at the connections between segments, but this model is limited in its ability to bend freely along the length. Another option for modelling a flexible shaft is to use a finite element model as in Nesbit (2005). This results in slow simulation times and is unsuitable for iterative optimization. A third model, proposed by Sandhu et al. (2010) uses Rayleigh beam theory to develop a computationally efficient dynamic simulation of a flexible shaft. This model allows the club's stiffness and moments of inertia (EI and GJ) to vary along the length of the shaft. This model was used by Sandhu as part of a kinematically driven driver model and was validated using player testing.

In this work, a 3-D forward dynamic golfer simulation similar to MacKenzie (2009) was combined with the Rayleigh beam model developed by Sandhu et al. (2010) for a flexible shaft. Optimized simulation code was created using the commercial MapleSim software package. The dynamics of four different flexible shafts were investigated, and comparisons were made between the optimal joint torques and swing outcomes for each shaft.

2. Methods

2.1. Model Description

A mathematical model of a golfer and club was constructed as a 3D multibody system. The golfer portion of the model was similar to that constructed by MacKenzie (2009). The golfer consists of 3 rigid bodies representing the torso, left arm, and hand. The torso is connected to the ground with a revolute joint and is allowed to rotate about an axis inclined 30 degrees from the vertical. The arm is connected using a universal joint (representing the shoulder) that allows both axial rotation (supination and pronation of the arm) and rotation in a swing plane inclined at 50 degrees from the vertical. Finally the hand is connected with a revolute joint that allows rotation in the same plane. The grip of the club is rigidly held in the hand. The golfer portion of the model has 4 degrees of freedom. The segment lengths, masses, and moments of inertia were the same as those used by MacKenzie except the mass and inertia of the hand was included as a separate body, not as part of the golf club. The golfer model is illustrated in Figure 1 and the segment properties can be found in Table 1. The mass properties for the rigid clubhead can also be found in Table 1.

Table 1 - Segment Properties for Golfer Model

Segment	Mass(kg)	Length(cm)	CM_x(cm)	CM_y(cm)	CM_z(cm)	I_x(kg cm^2)	I_y (kg cm^2)	I_z(kg cm^2)
Torso	34.61	20.0	0	0	0	--	3655	--
Arm	3.431	60.0	--	--	26.1	1076	1096	58.06
Hand	0.411	20.0	--	--	9.0	10.24	10.24	6.04
Clubhead	0.2	--	-6.35	2.65	-3.75	0.021	0.042	0.057

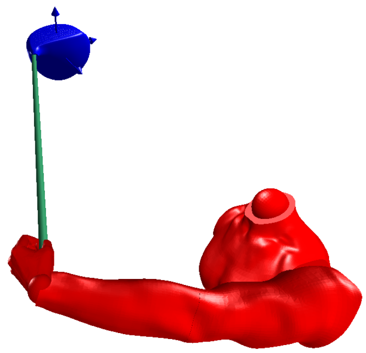

Figure 1 - Golfer and flexible club model near the top of backswing.

The input torques for the golfer model were defined by the same functions used by MacKenzie (2009a), taking into account both the activation and force-velocity curves of human muscles. Each torque generator is controlled by 5 parameters as shown in Table 2. The arm generator provides supination/pronation torques about the long axis of the arm while the shoulder generator provides torque to rotate the arm in the swing plane. The generated torque is calculated as follows. First the activation and deactivation of timing contribution is computed as:

$$T_{pre} = T_m(1-e^{-(t-t_{on})/\tau_{act}}) - T_m(1-e^{-(t-t_{off})/\tau_{deact}}) \tag{1}$$

Then, this value is scaled based on the fact that muscles cannot exert as much torque on limbs that are already moving quickly. As the angular velocity (ω) of the segment increases, the torque provided is decreased based on the following scaling:

$$T = T_{pre}\left(\frac{\omega-\omega_{max}}{\omega+\Gamma\omega_{max}}\right) \tag{2}$$

The muscle activation (t_{on}) and deactivation (t_{off}) times are set by an optimization process described below in section 2.3.

Table 2 - Muscle Activation Properties

Generator	T_m (Nm)	τact (s)	τ_{deact} (s)	Γ	ω_{max}(rad/s)
Torso	200	0.02	0.04	3.0	30
Shoulder	160	0.02	0.04	3.0	30
Arm	60	0.02	0.04	3.0	30
Wrist	90	0.02	0.04	3.0	30

2.2. Flexible Club

The flexible shaft used in the model is based on the work of Sandhu et al. (2010). The model uses a flexible Rayleigh beam (Shi et al. 1999) to describe the flexing and twisting of the club as it is swung. The approach makes use of a complete second-order elastic rotation matrix for a Rayleigh beam and has been implemented in the simulation package MapleSim. Shear due to bending and warping due to torsion are neglected, but the model can account for large deflections in the transverse directions that occur during the golf swing. The model can also account for changing stiffness, size, and density of material along the length of the shaft by defining each as a function of the length from the grip, x.

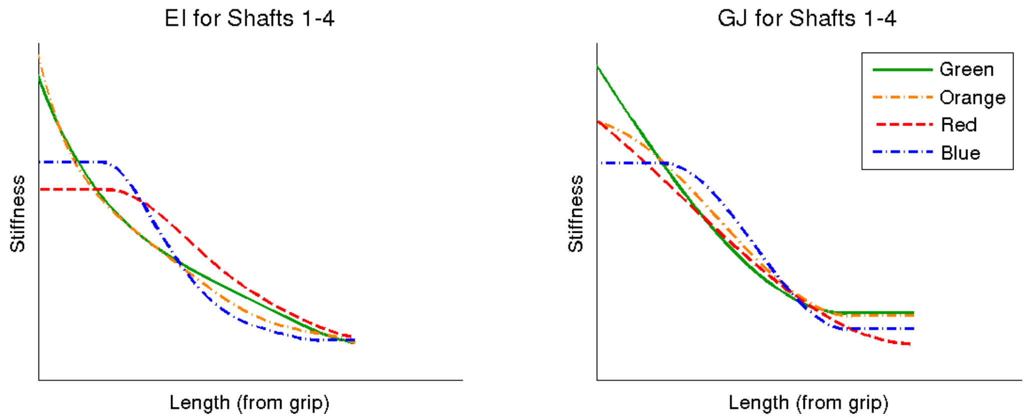

Figure 2 - Flexible shaft variable properties

In general, any particle of the flexible shaft can be located using four deformation variables: $u(x,t)$ for axial deformation, $v(x,t)$ and $w(x,t)$ for bending in the two transverse directions, and $\phi(x,t)$, the angle of twist about the centroidal axis. Deformation of the beam in each of these directions is approximated using Taylor series polynomials for the spatial variations, combined with a certain number of time-varying flexible coordinates for each of the four deformation variables. In this project, one flexible coordinate was used for the axial strain and twist, while two flexible coordinates were used for each of the transverse directions. As a consequence, $u(x,t)$ and $\phi(x,t)$ are spatially approximated with 2^{nd} order polynomials while the transverse coordinates $v(x,t)$ and $w(x,t)$ are approximated with 3^{rd} order polynomials.

For this work, four different club shafts and their material properties, measured using a custom cantilever test rig, were provided by a manufacturer. The cross-sectional area, Young's modulus, shear modulus, and second moment of cross-sectional area vary along the length of the club and are approximated using sixth-order polynomials. Normalized plots of the four clubs' stiffness properties are shown in Figure 2. Non-normalized data cannot be shown due to an agreement with the manufacturer. Examining this figure, we can say that the green and orange shafts have a smooth transition of club stiffness and have likely not been tuned. The red, and in particular the blue, shafts have sharp changes in their stiffness profiles or are more heavily tuned. The density (1510kg/m^3) and length of the shaft below the hands (0.91m) are also important parameters for the model.

Sandhu et al. (2010) validated the flexible club model with experimental testing and a finite element model of the shaft. This testing found good agreement between the dynamic loft, droop, and clubhead speed at impact, showing that the model is suitable for use in forward dynamic simulation.

2.3. Model Optimization

To perform a predictive, forward dynamic, simulation of the golf swing for the purposes of evaluating multiple flexible shafts it is not sufficient to use captured kinematic data to drive the flexible club, as Sandhu et al. (2010 have done. If the golfer is given a different shaft they may choose to swing differently from the captured data, or the golfer may not have been swinging optimally. To accommodate for changes in the swing caused by changes to the club, an optimization approach is used to find the 'best' swing for a given club.

In the optimization, the variables that can be changed are the four activation times (t_{on}) and four deactivation times (t_{off}) for the torque generators described in Section 2.1. The optimization seeks the best conditions for the clubhead at the time of impact with the ball. Launch conditions for the ball depend on the orientation of the club at impact, the attack angle (direction of the clubhead's velocity), the clubhead speed at impact, and the position of the impact on the clubface. The most important factor is the clubhead speed as it correlates directly with ball speed after impact (Lampsa, 1975). Since the ball can be placed at the 'sweet spot' of the face within the model, position of impact on the face is assumed to be ideal. We then assume that the best swing is characterized by a squared face at impact, a positive attack angle and maximum clubhead speed.

By changing the activation and deactivation times, the following objective function is maximized:

$$M = |V_{club}| - W_a|\Delta\Theta_\mathrm{a}| - W_{ha}|\Delta\Theta_\mathrm{ha}| - W_c|\Delta\Theta_c| - W_l|\Delta\Theta_l| \tag{3}$$

where V_{club} is the velocity of the centre of mass of the clubhead, $\Delta\Theta_\mathrm{a}$ is the magnitude of the attack angle outside the range of 2-6 degrees, $|\Delta\Theta_\mathrm{ha}|$ is the angle of the velocity vector from the down-range direction, $|\Delta\Theta_c|$ is the magnitude of the face angle (i.e. open or closed), and $|\Delta\Theta_l|$ is the magnitude of the dynamic loft outside the range of 10-15 degrees. W_a, W_{ha}, W_c, and W_l are weighting factors for the four penalty terms. This objective function will maximize the clubhead speed while minimizing the deviation from a square clubface at impact.

The optimization process was performed on the combined golfer and flexible club model using Matlab (2013). Optimized simulation code was exported from MapleSim (2013), and the Matlab command *fminsearch* was used to find the optimal muscle activation timings.

3. Results and Discussion

Figure 3(a) shows the joint angles for the torso, shoulder, and wrist for the blue (tuned) shaft. As observed before by Sharp (2009) and MacKenzie (2009a), the joint angles follow a proximal to distal progression: the torso begins to change its joint angle first, followed by the shoulder and then the wrists. The optimal muscle activations and joint torques that cause this motion are shown in Figure 3(b).The torso generator begins the motion, and then the shoulder and wrist are recruited to bring the club into position to hit the ball. The arm torque activates later in the swing to bring the face of the club square with the ball.

The velocity components for the blue clubhead are shown in Figure 3(c). Impact with the ball occurs 0.227s after the start of the simulation when the velocity in the Y and Z directions is close to zero and the velocity in the X direction is close to its peak. The clubhead speed at this point is 40.15 m/s, the face angle is 0.7 degrees, the dynamic loft is 15.28 degrees, the attack angle is -0.14 degrees, and the close angle is 0.7 degrees. The attack angle should be increased according to our criteria, but this may come at the expense of excessive dynamic loft in our model. Using the impact model found in Petersen & McPhee (2008) and the aerodynamic model of Quintavalla (2002), the blue club swing resulted in a drive carry distance of 185.06m with a lateral deviation of 1.9m.

In comparison to the other three clubs, the blue shaft had the highest clubhead speed at impact (40.15 m/s vs. about 39m/s) and dynamic loft (15.28 degrees vs. 13 degrees). Tests using the same impact and aerodynamic model resulted in ball carry distances ranging from 172-175m with deviations between 1.2m and 1.75m for the other shafts. *Simply by changing the shaft, the simulated golfer is able to lengthen their drive by about 10m without sacrificing accuracy*. The torques generated for the four different flexible shafts are shown in Figure 4. The torque profiles for the green, orange, and red clubs are very similar while the blue club has a different profile with an earlier activation of the shoulder and a later activation of the wrist.

The blue club's stiffness profile (see Figure 1) shows it was more heavily tuned than the other shafts. From the four shafts studied the shaft that was most heavily tuned was the best choice, resulting in the fastest clubhead speed and therefore the longest drives. This is not a general result for all golfers as it is specific to this model which attempts to mimic a golfer with average swing speed. Golfers who swing faster or slower than the model may be better suited to different shaft stiffness profiles. Shafts are often tuned for specific golfers, so if different muscle strengths were included in the model, the optimal shaft chosen may be different.

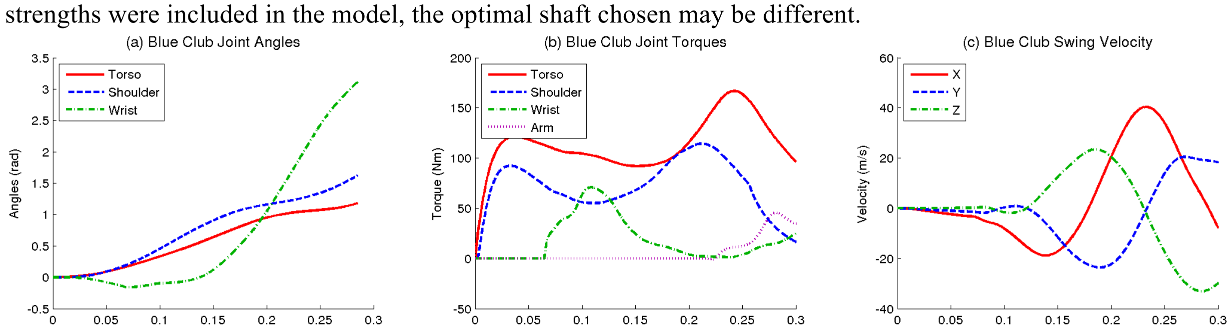

Figure 3- (a) Joint angles; (b) Velocity of clubhead CM; and (c) Torques generated for optimal swing with blue club

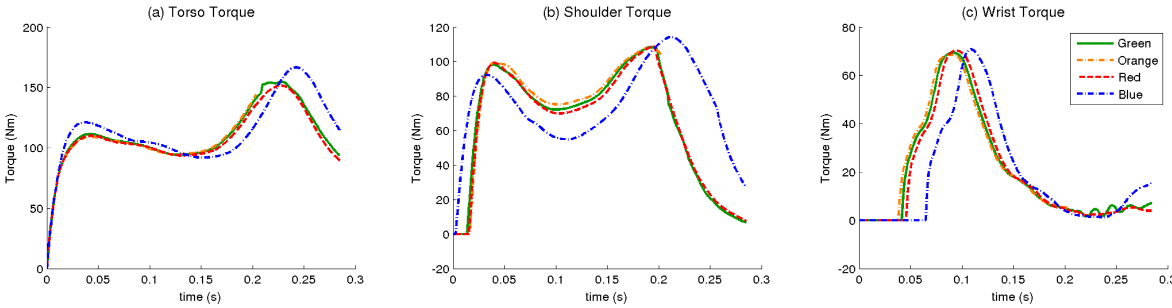

Figure 4 - (a) Torso torque; (b) Shoulder torque; and (c) Wrist torque generated for four different flexible shafts

4. Conclusion and Future Work

A 3D golfer model with realistic torque inputs, combined with a 3D flexible shaft model based on Rayleigh beam theory, was presented in the paper. The shaft model includes bending in both transverse directions along with axial strain and torsion, and can be used to model golf shafts with varying elastic properties along their length. An optimization approach was used to find the ideal torque inputs to the model. Simulations were used to examine four different flexible shafts and determine that for a golfer of average clubhead speed, it is possible to tune the bending profile of the shaft to deliver a higher-speed impact with the ball.

There is significant scope for further improvements to the model. The impact and aerodynamic models used to illustrate the results should be used in the optimization process to maximize driving distance rather than using an objective function based on the clubheadspeed and orientation at impact. ‘Stronger’ and ‘weaker’ golfers could be tested using the model by modifying the maximum torques that can be generated and their ‘best’ club selected from the pool of available drivers. In addition, the flexible club parameters could also be allowed to vary in the optimization, helping to design better flexible shafts for clubs.

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