A three-dimensional analysis of the forces and torques applied by a golfer during the downswing

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Teachers of golf need to have a thorough understanding of the mechanics of the swing. Cochran and Stobbs (1968) presented a comprehensive summary of some extensive testing performed by the Golfing Society of Great Britain. Their findings have undoubtedly led to a clearer understanding of the swing by scientifically-inclined golf instructors. One of Cochran and Stobbs' contributions was to popularize the concept of modelling a golfer's swing by the action of a planar double pendulum.

Several investigators have used the assumption of a two-dimensional pendular motion in an effort to understand the nature of the forces and torques applied to the club during the downswing. Williams (1967) used a stroboscopic photograph of Bobby Jones' swing and concluded that the uncocking torque applied by the hands was negligible. Jorgensen (1970) studied the same swing and suggested that the uncocking of the wrists should be delayed. Lampsa (1975) was interested in optimizing the control torques in order to increase clubhead velocity, while Budney and Bellow (1979) examined the effects of varying certain club parameters. In all of these studies it was assumed that the golfer's arms and club moved in the same plane throughout the downswing. The obvious appeal of the two-dimensional study is that it reduces both the data collection and analysis, as well as the mathematical complexity.

The purpose of the present study was to perform a three-dimensional investigation of the forces and torques applied to a golf club during the downswing. It was felt that a meaningful interpretation of these kinetic data would aid both the instructor and player in improving performance.

METHODS

Two leading professional golfers and two low handicap amateurs served as subjects. They were filmed by two orthogonally-placed motion picture cameras which operated at 300 frames/s and had exposure times of 1/800 s. The films were digitized on a Vanguard Motion Analyzer such that three separate points on the club could be determined in three-dimensional space. The inertial properties of the club were measured using standard compound and torsional pendulum techniques. These raw data were used as input for a FORTRAN program which incorporated the following mathematical model and performed time-differentiation by a cubic spline technique.

Figure 1 illustrates the reference systems that were used. $O:XYZ$ is an inertial frame that has a horizontal XY plane with Y axis passing through the midpoints of the golfer's feet. $C:xyz$ is a body-fixed reference frame with its origin embedded at the club's center of mass (C). Furthermore, xyz coincide with the club's principal axes of inertia at C. The unit vector $\hat{n}$ is normal to the "instantaneous plane" swept out by the club and is defined as follows: $\hat{r}$ is oriented along the shaft towards the golfer's grip, and $\hat{n}$ at time t_p is found by taking the cross-product of $\hat{r}$ at times t_{p-1} and t_{p+1}.

Application of Newton's second law to Figure 1 yields

$$\begin{Bmatrix} F_{AX} \\ F_{AY} \\ F_{AZ} \end{Bmatrix} = \begin{Bmatrix} m\ddot{X}_C \\ m\ddot{Y}_C \\ m\ddot{Z}_C + mg \end{Bmatrix} \tag{1}$$

where $\bar{F}_A = F_{AX}\hat{I} + F_{AY}\hat{J} + F_{AZ}\hat{K}$ denotes the resultant force applied to the grip at A by the hands, and $\hat{I}\hat{J}\hat{K}$ are unit vectors in the positive XYZ directions.

Taking moments about C gives

$$\begin{Bmatrix} T_{Ax} \\ T_{Ay} \\ T_{Az} \end{Bmatrix} = \begin{Bmatrix} T_x - aF_{Az} \\ T_y \\ T_z + aF_{Ax} \end{Bmatrix} \tag{2}$$

where $\bar{T}_A = T_{Ax}\hat{i} + T_{Ay}\hat{j} + T_{Az}\hat{k}$ denotes the resultant torque applied to the grip at A by the hands, and $\hat{i}\hat{j}\hat{k}$ are unit vectors in the positive xyz directions. The distance from point C to point A is denoted by a. The resultant torque $\bar{T}$ has components given by the Euler equations

$$\begin{Bmatrix} T_x \\ T_y \\ Z_z \end{Bmatrix} = \begin{Bmatrix} I_{xx}\dot{\omega}_x + (I_{zz} - I_{yy})\omega_z\omega_y \\ I_{yy}\dot{\omega}_y + (I_{xx} - I_{zz})\omega_x\omega_z \\ I_{zz}\dot{\omega}_z + (I_{yy} - I_{xx})\omega_y\omega_x \end{Bmatrix} \tag{3}$$

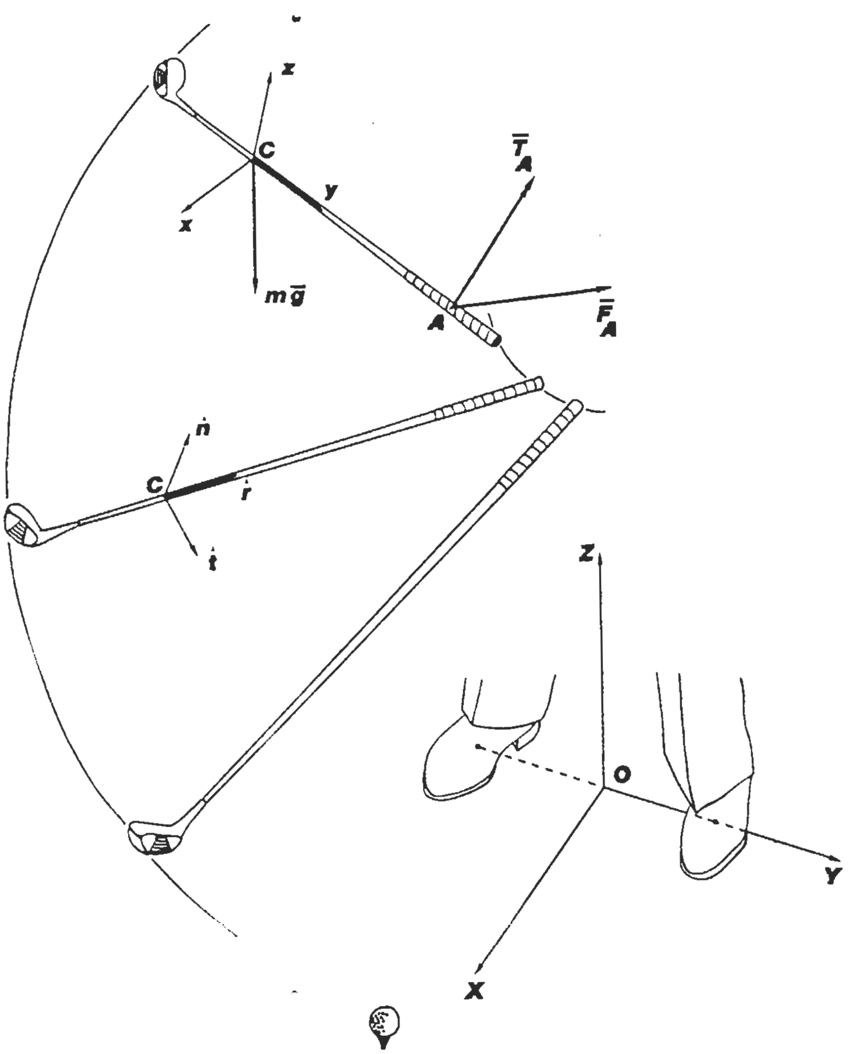

Figure 1. Free body diagram for the golf club. $\bar{F}_A$ and $\bar{T}_A$ are the resultant force and torque applied by the hands at A, while $m\bar{g}$ is the club's weight. Refer to the text for an explanation of the reference frames.

where the angular velocity ($\bar{\omega}$) and angular acceleration ($\dot{\bar{\omega}}$) of the club are expressed in terms of Euler angles and their derivatives (Synge and Griffith, 1959). Note that air resistance forces have been ignored and the club has been assumed to behave as a perfectly rigid body. It can be shown that these assumptions do not substantially alter the results (Budney and

Bellow, 1979). The applied force $\overline{F}_A$ and torque $\overline{T}_A$ were subsequently output relative to $\hat{n}\hat{t}\hat{r}$ in order to facilitate their interpretation and to compare with the two-dimensional findings of previous investigators.

RESULTS

The data presented in Figures 2, 3 and 4 constitute the major findings of the study. They are the data for one subject, but the results for the other three golfers were not markedly different.

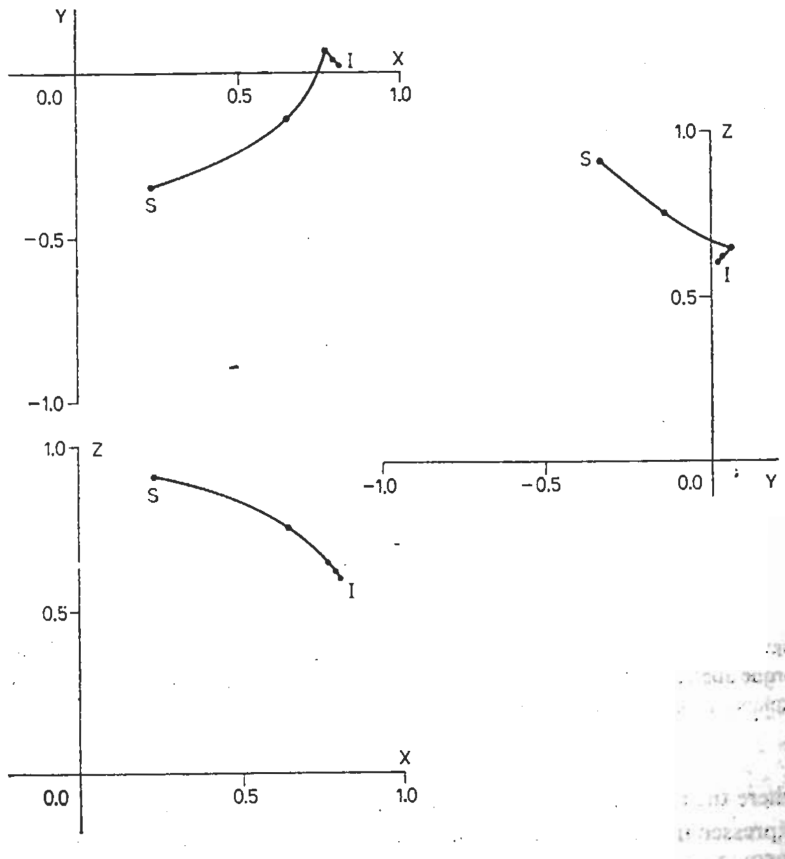

Figure 2. Variation of the instantaneous plane of the golf club (unit vector $\hat{n}$) in terms of the inertial reference frame $O{:}XYZ$. (Note: S—start of downswing; I—impact; the dots are 0.05 s apart.)

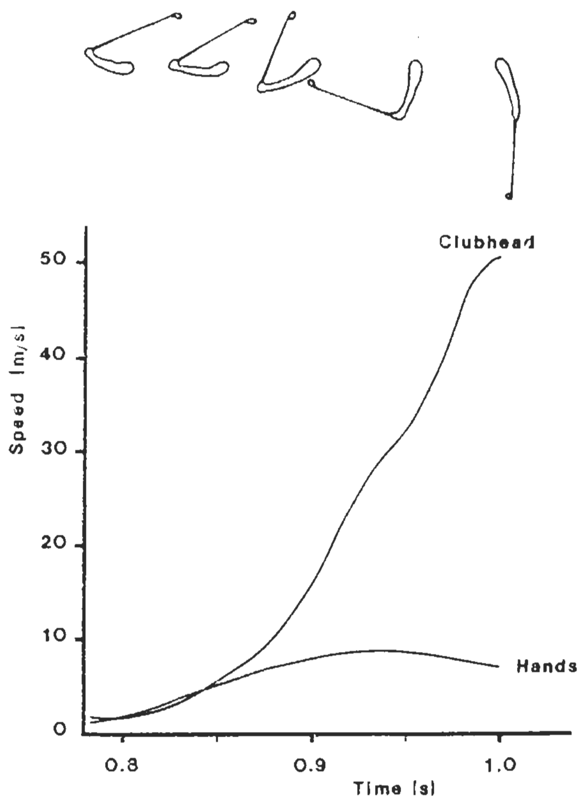

Figure 3. Speed of golfer's hands and clubhead. The sequence above the graph illustrates the position of the left arm plus club at equal time intervals. (Note: impact occurs at 1.0 s.)

Contrary to common belief, the plane of the shaft was *not* constant but varied during the early stages of the downswing (Figure 2). It would appear, however, that 0.1 s prior to impact the plane was fairly well established.

Figure 3 compares the speed of the golfer's hands and the clubhead. The sequence above the graph shows the left arm plus club viewed along the negative X axis. It is interesting to note that the hand speed *decreased* 0.06 s prior to impact while the clubhead speed increased rapidly during this latter period.

Figure 4 illustrates the $\hat{n}\hat{t}\hat{r}$ components of the resultant hand force $\bar{F}_A$ and torque $\bar{T}_A$ applied by the golfer at point A. The implications of these curves will be considered in the following section.

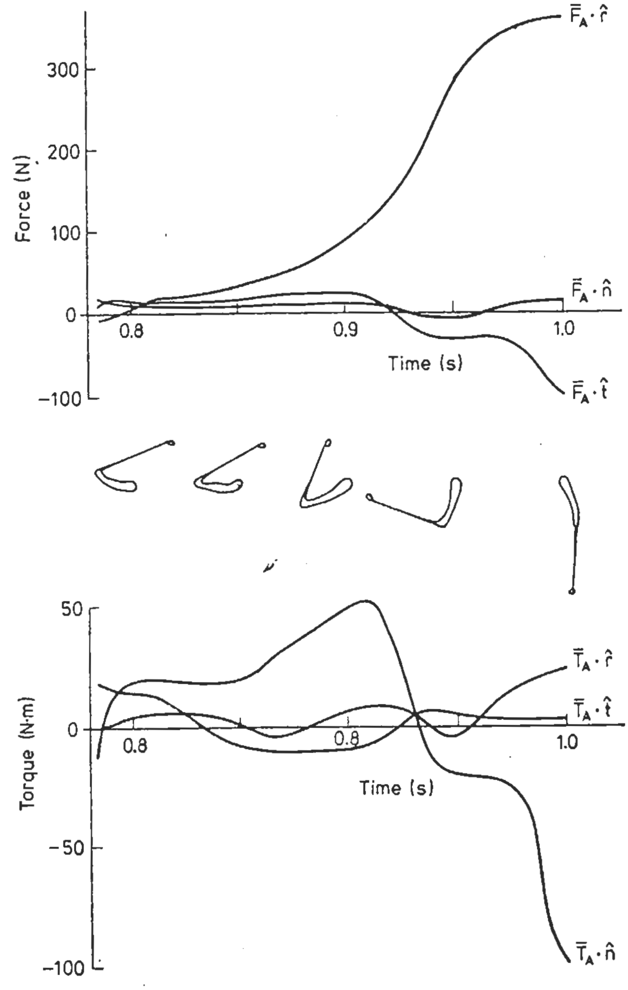

Figure 4. Applied forces and torques expressed relative to the instantaneous plane of the golf club. (Note: impact occurs at 1.0 s.)

DISCUSSION

The variation in the swing plane should be clearly evident from Figure 2. Despite this, however, the results for $\bar{F}_A \cdot \hat{t}$, $\bar{F}_A \cdot \hat{r}$ and $\bar{T}_A \cdot \hat{n}$ in Figure 4 are fairly similar to the findings of Budney and Bellow (1979) in a *Z-D* study.

In the past, the torque $\bar{T}_A \cdot \hat{n}$ has been associated with wrist action. In fact, both Lampsa (1975), and Budney and Bellow (1979), theorize that this torque should have a positive value throughout the downswing in order to achieve maximum clubhead velocity. However, it should be recalled that the golfer's two hands represent a distributed load system which has been reduced to an equipollent system of a single applied force and torque. It is not possible to determine the unique contribution at each wrist because techniques have not yet been developed for the calculation of joint torques in closed loop systems such as the arms and club in the golf swing. It should therefore be recognized that this normal torque cannot be considered as a valid measure of the cocking and uncocking action of the wrists.

A close examination of Figure 4 yields the following conclusions: (1) the downswing was initiated by pulling along the length of the shaft ($F_A \cdot \hat{r}$), and applying a positive hand torque ($\bar{T}_A \cdot \hat{n}$); (2) as the swing progressed, $\bar{F}_A \cdot \hat{r}$ increased markedly while $\bar{F}_A \cdot \hat{t}$ was applied in the opposite direction; (3) the result was decreased hand speed and increased clubhead speed, while a negative hand torque ($\bar{T}_A \cdot \hat{n}$) was invoked; (4) both $\bar{F}_A \cdot \hat{n}$ and $\bar{T}_A \cdot \hat{t}$ served to alter the swing plane during the early stages of the downswing, while $\bar{T}_A \cdot \hat{r}$ rotated the clubface into a square position at impact.

In this study the nature of the forces and torques applied to the club by the golfer has been examined. As such it provides a basis for future work directed towards an understanding of how the golfer himself generates these forces and torques.

REFERENCES

Budney, D. R., and D. G. Bellow. 1979. Kinematic analysis of a golf swing. Res. Quart. 50: 171–179.

Cochran, A., and J. Stobbs. 1968. The search for the perfect swing. J. B. Lippincott, Philadelphia.

Jørgensen, T. 1970. On the dynamics of the swing of a golf club. Am. Journ. Physics 38: 644–651.

Lampsa, M. A. 1975. Maximizing distance of the golf drive: an optimal control study. Journ. Dynamic Systems, Measurement and Control, Trans. A. S. M. E. 97G: 362–367.

Synge, J. L., and B. A. Griffith. 1959. Principles of mechanics. (3rd edition). McGraw-Hill Book Co., New York, N. Y.

Williams, D. 1967. The dynamics of the golf swing. Quart. Journ. Mech. and Applied Math. 20(2): 247–264.

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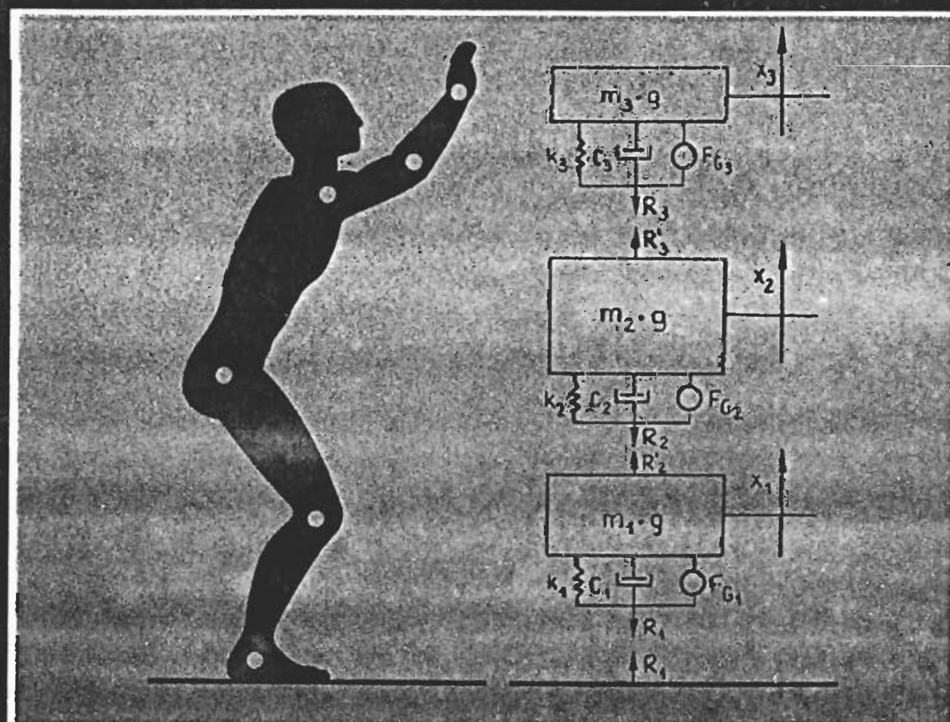

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