Segment interactions: Sequencing and Timing in the Downswing

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ABSTRACT

Golf coaches recognize that hitting great golf shots requires exquisite "timing" yet few people have tried to quantify this phenomenon and distinguish between well-timed (WT) and mis-timed (MT) shots. The purpose of this paper was to present a way of describing the timing in the golf downswing and investigate whether biomechanical variables could be used to evaluate the sequencing of movement during the swing. Three-dimensional kinematics for a five segment model of the body, coupled with carry distance and lateral error were collected as highly skilled players hit approximately 20 driver shots. Players rated each shot as being WT or MT. A method of describing sequencing was presented along with average values for the body segment speeds. Comparisons of the timing lags (i.e., the times between peak angular speeds of contiguous body segments) showed no significant differences between the WT and MT shots. It seems as though golfers are much more sensitive to the "centeredness" of contact than they are to subtle differences in the timing of peak body segment speeds.

Keywords: Kinematic sequence, timing, sequencing, segment interactions, movement patterns

INTRODUCTION

Golf requires that a player "control" the impact velocity of the club head. Most people recognize that club head speed is one of the determinants of success in this sport and so emphasis has been placed on finding movement patterns that result in high club head speed at impact. For throwing activities, of which golf is a sub-category, the preferred pattern of movement has been classified as a proximal-to-distal (PD) one. In this pattern, the "speed" of each segment in the kinematic chain increases as the movement plays out in time and as the segment gets "further" from the core of the body.

PD motion patterns have been the object of research scrutiny for almost 30 years when Bunn (1972) proposed the summation of speed principle in which the sequential order of any movement for maximal speed begins with the large, strong, proximal muscles followed by the small, weak, distal muscles. Postulates regarding the summation of speed, force and angular momentum in the sequencing of movement, all of which bear on the validity of the kinetic link theory (i.e., the notion of speed/energy/momentum transfer in a proximal to distal pattern), have been presented to account for specific empirical relationships between the mechanical variables implicated by the theory (Cavanagh and Landa, 1976; Hatze, 1976; Neal and Wilson, 1985, Milburn, 1982).

A number of these studies (Milburn, 1982; Neal and Wilson, 1985) have found qualitative evidence to support the summation of speed principle by noting that the peak angular velocity of the proximal segment was of lesser magnitude and occurred earlier in the action than its contiguous, distal segment (Roberts et al., 1985). Simulation experiments (Hatze, 1976; Sprigings and Neal, 2000) have also shown that optimal kinematics of the motion of two or three segment kinematic chains display this property. Unfortunately, little effort to quantify the length of time between these peak speeds or the energy that is transferred between the segments as a result of the motion dependent torques has been made in golf. Sprigings and Neal did indicate that changing the onset of the "muscle" torque by as little as 10 ms made a substantial difference (~10 kph) to simulated club head speed. Thus there is at least theoretical evidence to support the view that relatively small changes to the timing of segment involvement in fast actions such as the golf swing do have a marked effect on club head speed.

In summary, few findings have emerged that have been of practical significance to coaches and athletes. Whilst we recognize that proximal to distal movements are optimal, we still do not understand how long the delays or lags between peak segment speeds should be. Specific to golf, we have yet to gain a clear understanding of the differences in timing patterns (and therefore energy flow) between well-timed and mis-timed golf shots. Lastly, and from a practical or applied perspective, it is crucial to understand how coaching input, biofeedback and altered physical properties of the performer such as flexibility, strength and stability can change the timing structure of the golf swing.

Thus, the purpose of this study was to elucidate the differences in sequencing and timing of body segment velocities between the well-timed (WT) and mis-timed (MT) shots. A secondary purpose was to develop a "model" set of speed and timing intervals to which coaches can compare their golfers.

METHOD

Participants

Thirteen male and twelve female golfers, recruited from the Australian Institute of Sport (AIS) and Victorian Institute of Sport (VIS) Golf Programs and the Victorian State squads, participated in the study. All golfers were aged between 16 and 35 years; informed, written consent was obtained prior to testing. This group represented a highly skilled population of amateur golfers. Participants attended one testing session in which they were asked to strike 25 – 30 golf shots with a driver. After striking each shot, subjects were asked to qualitatively describe the timing as excellent, poor, or average. A minimum of 10 shots that they described as "well- timed" and between 5 and 10 shots in which the timing was less than optimal ("mis-timed") were captured.

Study Design

Biomechanical Analysis

Three dimensional (3D) kinematic data were obtained through the use of a Polhemus Fastrak magnetic tracking system (Polhemus Inc., Colchester, VT). This system provides real-time position (XYZ coordinates) and orientation data (Euler angles) of sensors attached to various body segments. The quoted accuracy of this system is better than 1 mm for translations and 1° for orientations. Segment position and orientation data were captured for approximately 2 s for each swing with each sensor sampled at 30 Hz.

A four-sensor system was used to provide position and orientation data for a five-segment model of the golfer. Higher-order kinematic data were calculated using standard numerical differentiation procedures. The segments in this model included the pelvis, upper torso, left arm, left forearm, and left hand (for a right handed golfer) and sensors were attached to the following locations:

1. Top of the sacrum (at the level of S1) to monitor the motion of the pelvis
2. Top of the thoracic spine (at the level of T2) to monitor the motion of the upper torso
3. The left arm (just above the elbow) to monitor the motion of the arm
4. The left hand (posterior surface of the metacarpals) to measure the motion of the hand

Subjective error, introduced when placing sensors on these locations, was minimized by having the same experimenter carry out sensor placement across all trials. Furthermore, a local, anatomically relevant coordinate system (see below) was defined for each segment in the model based on the location of distinct anatomical landmarks on each segment relative to the sensors attached to the body. As both the wrist and elbow joints are two degree of freedom joints, a fifth (virtual) marker attached to the forearm was simulated using standard mechanics principles. Thus, the motion of the forearm was predicted on the basis of the motion of the two adjoining segments (i.e., the arm and the hand).

Prior to collecting data, a digitization procedure was carried out to develop the transformation matrices necessary to describe anatomically referenced local coordinate systems in each body segment. On the basis of the position and orientation of the sensors attached to the body and the position of these landmarks, vectors were defined along the principle axes of each of the segments. The origin of each of these local coordinate systems was at the centre of the proximal joint (e.g., the arm segment origin was located at the shoulder joint). Standard matrix algebra was used to transform data from the measured (sensor) coordinate systems to the anatomical coordinate systems. These transformations were applied to the complete time series data.

A sound activated switch, synchronized with the Polhemus Fastrak system, was used to accurately determine the instant of impact. The timing pulse available from the Fastrak system and a voltage emanating from the switch were simultaneously collected using a 2-channel A/D converter. Data were time interpolated (cubic spline) so that all samples were synchronized to impact. The top of the backswing was defined as that point when the pelvis reached its minimum rotation around its long axis.

The kinematic variables derived from biomechanical analysis included the peak segmental angular velocities and their times of occurrence as well as the timing lags between these peaks. Angular velocities were calculated and are reported with respect to the local coordinate systems embedded in the segments. In these coordinate systems, the velocities represent the rates of flexion/extension (around the x-axis), tilting/lateral bending or radial-ulna deviation (around the y-axis) and axial rotation (around the z-axis or long axis of the segment). In an effort to help simplify the data, the resultant angular speed (independent of direction) for each segment was calculated. The results primarily relate to these data with the notable exception of the hand for which data on both the local x-axis (i.e., the component perpendicular to the palm of the hand) and the local z-axis (i.e., the pronation velocity component of the forearm) are presented. The linear velocity of the hand and the time of occurrence of its peak component along the X-axis (target line) were also determined. Many of these variables are illustrated graphically in Figure 1, which shows the average sequencing graph for the males and females.
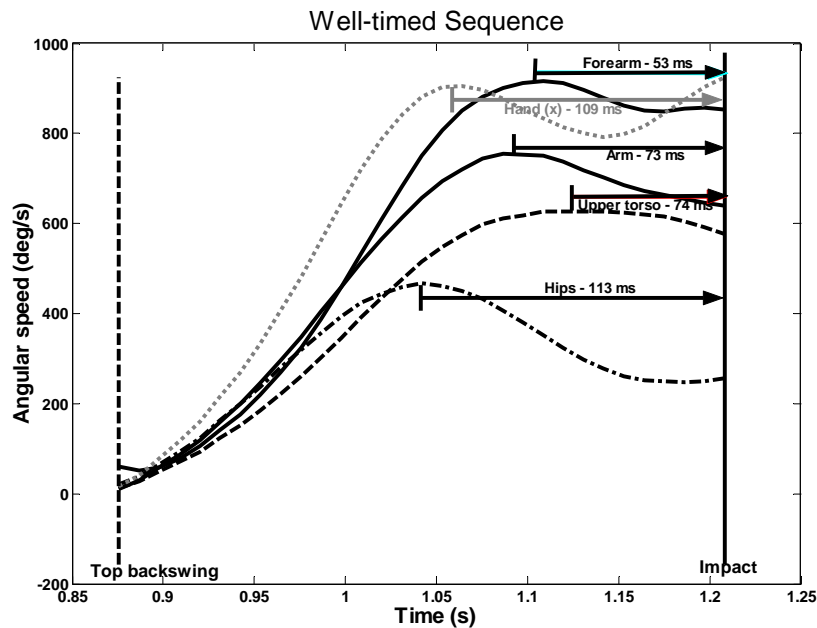
Figure 1. Angular speeds of the five segments (pelvis, upper torso, arm, forearm and hand) between the top of the backswing and impact. The peak values are highlighted along with the times from the peaks to impact.

Digital processing

Data were submitted to customized software designed to calculate both kinematic and temporal data. Shannon's re-sampling algorithm (Hamill et al., 1997) was applied to reconstruct the time-series data at a sampling frequency of 360 Hz. Data were smoothed using a Butterworth 2nd order digital filter with a 15 Hz cut-off frequency.

Performance Data

Ball flight and trajectory were qualitatively monitored and recorded. The distances that the ball travelled through the air (carry distance) as well as the perpendicular distance from the point of landing to the intended target line were measured (Bushnell Pinseeker® 1500).

Statistical Analysis

Student's t-tests were applied to the data to determine if there were differences between the timing lags, times of peak speeds and the peak speeds of the well-timed versus mis-timed shots. Statistical significance level was set at the $p < .05$ level. Group mean and variance data were also calculated across subjects for all dependent variables to determine a general model of swing sequencing and timing variables. Since multiple comparisons were made, a Bonneferoni correction to the alpha level was applied to reduce the likelihood of making a Type I error.

RESULTS

Descriptive characteristics for subjects are presented in Table 1. The group of subjects was highly skilled with handicaps ranging from -3 to +2.

Table 1. Mean (SD) age, height, mass and handicap of the subjects

	N	Age (yr)	Height (cm)	Mass (kg)	Handicap
Males	13	19.8 (1.4)	184.3 (7.2)	82.3 (14.8)	+1.0 (1.1)
Females	12	21.0 (4.5)	173.2 (5.9)	66.6 (5.5)	-1.3 (10.4)

Grouped Data

Mean data are presented below for the peak angular velocities, hand linear velocity in the direction of the target, carry distances and lateral error (Table 2), the times of peak angular velocities prior to impact (Table 3), and the lag times between peaks (Table 4).

Despite both carry distance and the lateral error being significantly different ($p < 0.05$) between WT and MT trials, there were no significant differences observed in kinematic variables of the grouped data. There was greater variability in the kinematic and temporal measures in the MT trials compared to the WT data, as shown by the slightly higher standard errors.

Table 2. Mean (SD) peak angular speeds, carry distances and lateral errors

	PSPEL (deg/s)	PSUT (deg/s)	PSA (deg/s)	PSFA (deg/s)	PSH_{ang} (deg/s)	PSH_{lin} (cm/s)	CD (m)	TL (m)
WT	479 (54)	660 (54)	814 (41)	900 (27)	962 (14)	474 (68)	230 (27)	8 (14)
MT	479 (68)	660 (81)	816 (54)	895 (41)	963 (14)	474 (81)	222 (41)	20 (27)

Key: **PSPEL** – peak angular pelvic speed; **PSUT** – peak angular upper torso speed; **PSA** – peak angular arm speed; **PSFA** – peak angular forearm speed; **PSH$_{ang}$** – Peak angular hand speed; **PSH$_{lin}$** – peak linear hand speed; **CD** – carry distance; **TL** – lateral error of the shot

Table 3. Average (SEM) times (ms) from peak angular velocity of the five segments to impact.

	PEL	UT	ARM	FA	H(z)	H(x)	H(lin)
WT	115 (27)	81 (27)	78 (27)	36 (41)	1 (0)	107 (27)	56 (27)
MT	114 (27)	73 (41)	76 (27)	32 (54)	1 (0)	106 (27)	55 (27)

Key: **PEL** – pelvis; **UT** – upper torso; **ARM** – upper arm; **FA** – forearm; **H(z)** – hand (component about the z-axis of the hand local coordinate system); **H(x)** – hand (component about the x-axis of the hand local coordinate system); **H(lin)** – hand (linear speed)

Table 4. Mean (SEM) lag times (ms) between segment angular velocity peaks

	P-UT	UT-A	A-FA	FA-H(z)	FA-H(x)	H(z)-I	H(x)-I
WT	37 (27)	6 (27)	45 (41)	39 (41)	-70 (41)	1 (0)	107 (27)
MT	37 (41)	7 (41)	46 (54)	35 (54)	-74 (41)	1 (0)	106 (27)

Key: **P-UT** – pelvis to upper torso; **UT-A** – upper torso to arm; **A-FA** – arm to forearm; **FA-H(x)** – peak forearm to peak hand angular velocity (around local x-axis); **FA-H(z)** –peak forearm to peak hand angular velocity (local z-axis); **H(x)-I** – peak hand angular velocity (local x-axis) to impact; **H(z)-I** –peak hand angular velocity (local z-axis) to impact;

DISCUSSION

When subjects were chosen for this study it was thought that this cohort would provide sufficient variability in their timing so that both well-timed and mis-timed data were available for analysis. The data do not bear out our initial assumption since there were no significant differences in the timing parameters between the well-timed and mis-timed shots. Our interpretation of this finding is that despite the differences in the result of the shots (i.e., carry distance and lateral error), there were no differences in the way in which speed was built up by the body. Thus, the performance difference was due to differences in the point of impact of the ball on the club face, as well as small changes in the orientation of the club face at impact. It has been well understood that "off-centre" impacts make a substantial difference in the overall carry and roll distances of a golf ball (Cochran and Stobbs, 1968).

Secondly, our classification of well-timed and mis-timed shots was based on player judgment and carry distance. This group of athletes probably based their decisions on the feel,

sound and "centeredness" of contact rather than on whether their timing was good or poor. This hypothesis seems quite reasonable since these golfers are extremely consistent with their body movements and the usual criterion that is proffered by high-level golfers on the quality of a golf shot is how they felt about the contact that they made with the golf ball. Clearly the balls that were judged by the athletes as being well-timed carried further and were closer to the desired target line than the mis-timed shots. Unfortunately information on club head velocity (speed and direction) immediately prior to impact, impact position of the ball on the clubface, as well post-impact ball velocity and spin were not measured. Further, it is rare that golfers are given feedback on their timing and thus are likely to have no or little experience in judging the quality of their timing. They are left to rely simply on how the contact felt and then how the ball flew!

During the course of this project, it was deemed important to differentiate between the terms sequencing and timing. We chose to define sequencing as a way of describing when the different segments of the body began to move faster than the adjoining one. For example, getting the sequence of the downswing in the correct order would see the lower body's rotation toward the target begin before the upper body's rotation. Timing on the other hand was used to define the epochs between peak speeds of the segments and relative to impact. Thus it is possible for a golfer to show correct sequence of movement with poor timing but the converse, incorrect sequence and good timing, is not possible.

One important finding that also emerged was that different "timings" were observed depending on which angular velocity component was studied. We found that the peak of the axial rotational speed of the hand occurred at a different point in the downswing compared to the peak of the rate of ulna/radial deviation at the wrist. The time of the peak rate of wrist deviation occurred, on average, 100 ms before impact whereas the peak axial speed of the hand occurred virtually at impact (< 2 ms prior to contact). Thus the peak wrist uncocking speed (as defined classically in the literature) which corresponds to the rate of wrist deviation occurs nearly 100 ms earlier in the downswing than the peak axial rotation as the club face is squared up for impact.

APPLICATION

Golf coaches and players need to be taught a new and complete understanding of timing in the golf swing. The term "lag", as it is currently used by golf professionals, is much too vague and ambiguous. It is currently used nebulously to refer to the point in the swing when the wrists begin to uncock. This study has revealed that there are distinct time gaps between the peak angular velocity of the different body segments and that these epochs are crucial to an effective golf swing. Golf coaches need to learn these definitions and then be able to modify the timing signatures to improve the efficiency of their students' swings.

There are timing patterns that are more efficient than others. For example, poor amateur players typically show no lag between the peak speeds of the pelvis and the upper torso and their hands attain their peak speed well before impact (meaning that they are slowing down too soon). The likely consequence of this phenomenon is that the club head too will have reached its peak speed before impact and be slowing down prior to ball contact. In our ideal timing model, there is a progressive increase in the peak speeds of the body segments as one moves from the pelvis, to

the upper torso and finally out to the hands. There are also very consistent times or epochs between these peak speeds (see Table 4) that are indicative of a well-timed swing.

One of the objectives of this research was to describe and present a method of evaluating "timing" during the golf swing. Figure 1 actually depicts this method in which the angular speeds of key body segments are plotted as a function of time during the downswing. These data show that there is a proximal-to-distal pattern in which peak speeds of the large segments that are close to the core of the body reach their peak speeds first and are slower than the small, distal segments. Thus, qualitative observation of this figure illustrates that the peak speeds of the distal segments occur closer and closer to impact as the downswing plays out. The deceleration following the peak speed could be due to the acceleration of the next (distal) segment in the chain and is worthy of further investigation.

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