Body Segment Sequencing and Timing in Golf

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ABSTRACT
Hitting great golf shots requires, in coaching terms, exquisite "timing". Despite this criterion, 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 and shot 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 and average values for the body segment speeds were presented. 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 "centredness" of contact than they are to subtle differences in the timing of peak body segment speeds.

Key words: Biomechanics, Kinematic Chain, Summation of Speed Principle

INTRODUCTION

Most ball sports have, as one of their determinants of success, a requirement to move an implement or object at high speed. Humans have learned that an ordered sequence

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of body segment involvement is a pattern of movement that produces high speed (and reasonable accuracy) at the most distal end of a kinematic chain. For example, in tennis and golf, the extension of the legs, rotations of the torso and various extensions and rotations of the joints of the upper limb lead to high racquet/club head speeds when ball contact is made. These patterns of movement have been classified generally as proximal-to-distal (PD) motion patterns.

PD motion patterns have been the object of research scrutiny for over three decades after Bunn [1] 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 [2, 3, 4, 5].

A number of these studies [4, 5] 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 [6]. Simulation experiments [3, 7] 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 & Neal [7] 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.

Considerable research effort has also been directed to understanding the way in which 'motion-dependent torques' influence movement patterns. That is, it has been commonly thought that the proximal segment slows down so that the adjoining, distal segment can accelerate past it. This notion may not be true and its slowing may be a consequence of the reaction torques produced by the motion-dependent torques of the distal segment.

Putnam [8, 9] initiated this work by re-organising the typical Newtonian equations of motion into subsets that were dependent on the motion (i.e., angular velocity, angular acceleration, linear velocity) of the adjoining segments as well as gravity. This work revealed that the motion-dependent torques were very important in determining the pattern of movement that emerged. For example, the torque due to the angular velocity of the adjoining segment was maximised when the orientation angle between the two segments was 90º but that the torque due to the angular acceleration was zero in this orientation. Conversely, when the angle between the segments was at 180º (i.e., the segments were parallel to each other) the opposite was the case! Whilst her work initially focused on punt kicking, Hoy and Zernicke [10] looked at the swing phase of feline gait. The method has subsequently been used for other activities including Taekwondo [11, 12].

Recent work using this framework [12, 13] has quantified the influence that motion of the club has on the upper arm and in turn, the influence that the upper arm has on the motion of the upper torso. The many interactions possible amongst three (as opposed to earlier work using only two segments) makes the task of teasing out how each motion-dependent torque influences the other segments' motion extremely challenging.

A fundamental question that arose out of this work on segment interactions related to understanding why the proximal-to-distal motion pattern was the preferred one adopted by highly skilled performers when they performed fast, swinging actions. Neal & Sprigings [14] postulated that the force-velocity property of human muscle was a constraint that had not previously been accounted for in earlier modelling work and that it dictated that a PD sequence was necessary to produce maximum speed.

In summary, whilst considerable research effort has been directed toward timing and sequencing of the segments involved in a complex movement, few findings have emerged that have been of practical significance to coaches and athletes. Whilst we recognise 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 mistimed 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 mistimed (MT) shots. A secondary purpose was to develop a "model" set of speed and timing intervals to which coaches can compare their golfers.

METHOD

SUBJECTS

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.

STUDY DESIGN

Participants attended one testing session in which they were asked to strike 25 – 30 golf shots with a driver, as they would when playing golf, while 3D kinematic data were recorded. 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 & 10 shots in which the timing was less than optimal ("mistimed") were captured such that differences between the measured variables describing the well-timed and mistimed swings could be evaluated. Testing sessions were carried out at the AIS training facility at Moonah Links, Victoria.

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 has been used extensively in golf applications and 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^{o} 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:

- Top of the sacrum (at the level of S1) to monitor the motion of the pelvis
- Top of the thoracic spine (at the level of T2) to monitor the motion of the upper torso
- The left arm (just above the elbow) to monitor the motion of the arm
- 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 minimised 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 each have two degrees of freedom, 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 digitisation 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, synchronised 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. An interpolating cubic spline was fitted to each of the 6 degrees of freedom of the kinematic data from each sensor and 'new' data points were created, synchronised to the instant the ball was struck. 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-ulnar 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.

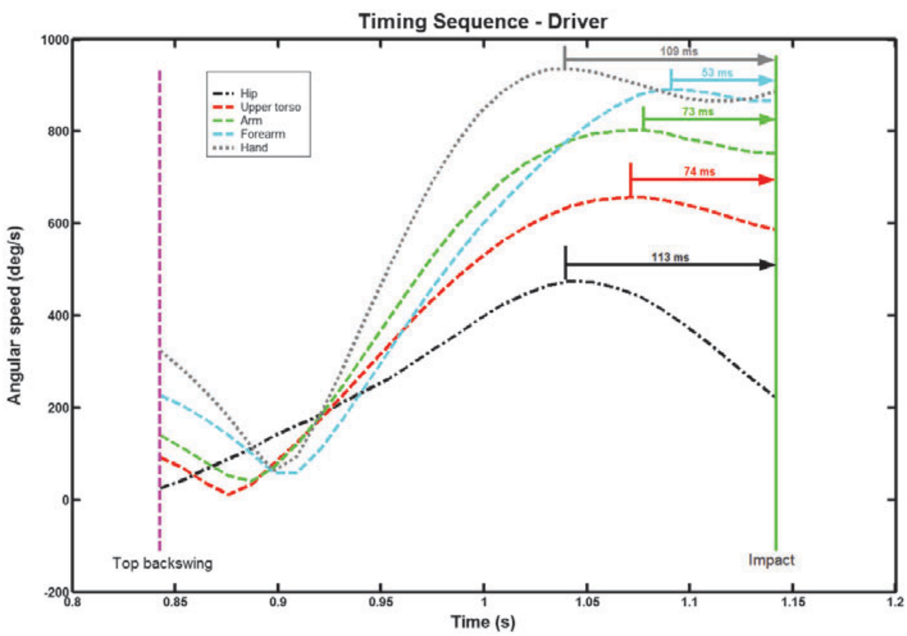

Figure 1. Angular Speeds of the Five Segments (Pelvis, Upper Torso, Arm, Forearm and Hand) Between the Top of the Backswing and Impact

The peak values are highlighted along with the times from the peaks to impact.

DIGITAL PROCESSING

Data were submitted to customised software designed to calculate both kinematic and temporal data (see tables below). Once the point of impact was determined, all data were time-shifted relative to that instant and then Shannon's re-sampling algorithm

[15] was applied to reconstruct the time-series data at a sampling frequency of 360 Hz. Data were smoothed using a Butterworth 2^{nd} order digital filter with a 15 Hz cut-off frequency. Prior to smoothing, data endpoints were extrapolated 40 samples before and after the first and last data points respectively. These extra points were removed prior to analysis. The critical event samples were determined for each trial using many of the principles described by Neal [16, 17].

PERFORMANCE DATA

Together with kinematic variables, the ball flight and trajectory were qualitatively monitored and recorded. The distance that the ball travelled through the air (carry distance) was also measured using a laser measuring device (Bushnell Pinseeker® 1500), as was the distance from landing location of the ball to a marker located on the target line, 220 meters from the tee. The perpendicular distance from the point of landing to the intended target line was then determined from these data.

STATISTICAL ANALYSIS

Since the purpose of the study was to determine if there were differences in the timing and sequencing variables of well-timed and mistimed golf shots, statistical analysis reflected this objective. Thus, 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 dependent variables. 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 Bonferroni 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 amateur golfers, with handicaps ranging from -1 to +2 for the males and from -3 to +1 for the females. The group of subjects was also relatively homogeneous in terms of their age, height, and weight. It was believed that this group of subjects would provide sufficient diversity in shot production (i.e., both well-timed and mistimed shots).

Table 1. Mean and Standard Error of Mean for Age, Height, Mass and Handicap of the Subjects

	N	Age (yr)	Height (cm)	Mass (kg)	Handicap
Males	13	19.8 (0.4)	184.3 (2.0)	82.3 (4.1)	+1.0 (0.3)
Females	12	21.0 (1.3)	173.2 (1.7)	66.6 (1.6)	-1.3 (0.4)

GROUPED DATA

Group mean data are presented below for the peak angular speeds, hand linear speed 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).

Table 2. Mean and Standard Error of Mean for Peak Angular Speeds, Carry Distances and Lateral Errors

		PSPEL (deg/s)	PSUT (deg/s)	PSA (deg/s)	PSFA (deg/s)	PSHang (deg/s)	PSHlin (cm/s)	CD (m)	TL (m)
Males	WT	488 (3.8)	671 (4.2)	819 (2.9)	895 (2.2)	945 (1.1)	490 (4.7)	258 (1.8)	9.1 (0.95)
	MT	487 (5.0)	670 (5.5)	821 (3.5)	889 (2.9)	946 (1.4)	489 (6.1)	248 (2.5)	23.2 (1.65)
Females	WT	469 (4.1)	648 (2.8)	809 (2.2)	905 (2.8)	979 (1.3)	457 (4.3)	202 (1.7)	6.3 (0.63)
	MT	470 (5.3)	648 (2.9)	811 (2.9)	900 (4.4)	979 (1.8)	459 (5.8)	195 (2.2)	15.5 (1.28)

Key: PSPEL – peak angular pelvic speed; PSUT – peak angular upper torso speed; PSA – peak angular arm speed; PSFA – peak angular forearm speed; PSHang – Peak angular hand speed; PSHlin – peak linear hand speed; CD – carry distance; TL – lateral error of the shot

Table 3. Mean and Standard Error of Mean Times (ms) for Peak Angular Velocity of the Five Segments to Impact

		PEL	UT	ARM	FA	H(z)	H(x)	H(lin)
Males	WT	113 (2.0)	74 (2.2)	73 (1.8)	53 (2.8)	1 (0.2)	109 (1.5)	48 (1.5)
	MT	114 (2.6)	74 (3.1)	73 (2.3)	46 (3.8)	1.(0.2)	108 (1.8)	48 (1.8)
Females	WT	116 (2.1)	88 (1.8)	83 (2.3)	19 (2.2)	0 (0.0)	105 (1.5)	63 (1.4)
	MT	114 (2.6)	87 (2.4)	79 (3.4)	18 (2.9)	0 (0.0)	104 (2.1)	61 (1.9)

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 and Standard Error of Mean Lag Times (ms) Between Segment Angular Velocity Peaks

		P-UT	UT-A	A-FA	FA-H(x)	FA-H(z)	H(x)-I	H(z)-I
Males	WT	42 (2.2)	3 (2.2)	23 (3.4)	55 (2.8)	-56 (2.6)	1 (0.2)	109 (1.5)
	MT	43 (2.8)	3 (2.7)	29 (4.4)	49 (3.7)	-62 (3.4)	1 (0.2)	108 (1.8)
Females	WT	31 (1.9)	8 (1.5)	66 (2.8)	22 (2.2)	-85 (1.9)	0 (0.0)	105 (1.5)
	MT	30 (2.5)	11 (2.6)	63 (4.1)	21 (2.9)	-85 (2.3)	0 (0.0)	104 (2.1)

Key: P-UT – pelvis to upper torso; UT-A – upper torso to arm; A-FA – arm to forearm; FA-H(x) – lag between peak forearm and peak hand angular velocity about the local x-axis; FA-H(z) – lag between peak forearm and peak hand angular velocity about the local z-axis; H(x)-I – lag from peak hand angular velocity about the local x-axis to impact; H(z)-I – lag from peak hand angular velocity about the local z-axis to impact

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 higher standard errors.

Of interest from a practical perspective is the observation that peak angular velocities of the forearm and hand of the female subjects was greater than their male counterparts ($p < .05$), whilst peak linear speed of the hand was lower and occurred much earlier in the downswing than male subjects. The peak angular velocity of the pelvis and upper torso was significantly greater ($p < .05$) in the male subjects compared to the females and probably reflects differences in their strength and power.

DISCUSSION

When selecting the subjects for this study, it was important to choose players who would demonstrate both well-timed and mistimed shots. This cohort of young amateur players seemed a good choice since their swings were not as well-learned as touring professionals and therefore they would be likely to hit poor shots as well as very good ones. The data do not bear out our initial assumption, however, as there were no significant differences in the chosen parameters between the well-timed and mistimed shots. A number of reasons for this finding seem viable. Firstly, it could be cogently argued that despite the differences in the result (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 [18].

Alternatively, it is possible that the selected variables were not sensitive enough to pick out subtle differences in the timing patterns. In contrast to this statement, our unpublished work with much poorer players indicates that the measures used to quantify the sequencing and timing of body segment motion are quite sensitive to timing errors. For example, many amateur golfers with "poor" golf swings show patterns of speed build-up where the rotational speed of the upper torso precedes that of the pelvis. Others show patterns in which the hands, upper torso and pelvis all peak simultaneously. Thus, it seems reasonable to conclude that the variables used to describe sequencing and timing are sensitive to timing differences.

Finally, our classification of well-timed and mistimed shots was based on player judgement and carry distance. Perhaps this group of athletes based their decisions on the feel, sound and "centeredness" of contact rather than on whether their body sequence 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 mistimed 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. Our suspicions are that the subjects' judgement of how well the shot was timed was based predominantly on the centeredness of the contact and/or the result of the shot rather than being truly indicative of how well they sequenced and timed their body segment movements. This contention is largely based on the experience gained through working with golfers of all abilities where timing data have been collected on a smaller number of body segments. These data show no statistically significant differences between well-hit versus poorly hit shots. Further, it is rare that golfers are given feedback on their timing sequence and thus are likely to have no or little experience in judging the quality of their sequence. 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. *Sequencing* refers to the relative displacements of the body segments: that is, does the movement of one segment precede that of its contiguous neighbour. *Timing* on the other hand was used to define the epochs between peak speeds of the segments. 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.

While recognising that there were no significant differences identified in most of the comparisons, when individual trials were examined qualitatively and the "best" shot of each subject was compared to the "worst" one, some interesting observations emerged. The most notable of these was the way in which the timing between the upper torso and pelvis was altered. In the poor shot, the pelvis reached its peak speed much earlier in the downswing (i.e., further from impact) with a higher speed than the best shot. The speed of the upper torso in the best shot was higher than the worst shot. These observations were consistent with the phenomenon that coaches refer to as "being connected". In the poor shot, the pelvis raced ahead of the upper body that was never able to "catch up" to ensure good impact posture. With the best shot, the upper body did not ever get "left behind" by the pelvis and was therefore able to achieve a greater speed, closer to impact than the bad shot. These types of observations are illustrated by the data depicted in Figure 2 where the best and worst trials from one subject are plotted.

Anecdotal evidence was also shown to support the notion that physical limitations (e.g., muscle weakness or poor flexibility) often underpin some of the sequence and timing errors found. For example, some of the young female golfers showed relatively slow arm, forearm and hand speeds when compared to their fast body speeds. Subsequent muscle testing showed that they lacked strength of the upper back and shoulders and had poor scapular stability and control. Thus, their physical capabilities had a marked effect on their timing signature.

One important finding that also emerged was that different timing signatures were observed depending on which angular velocity component was studied. We found that the peak of the axial rotational speed of the hand (i.e., pronation/supination) occurred at a different point in the downswing compared to the peak of the rate of ulnar/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

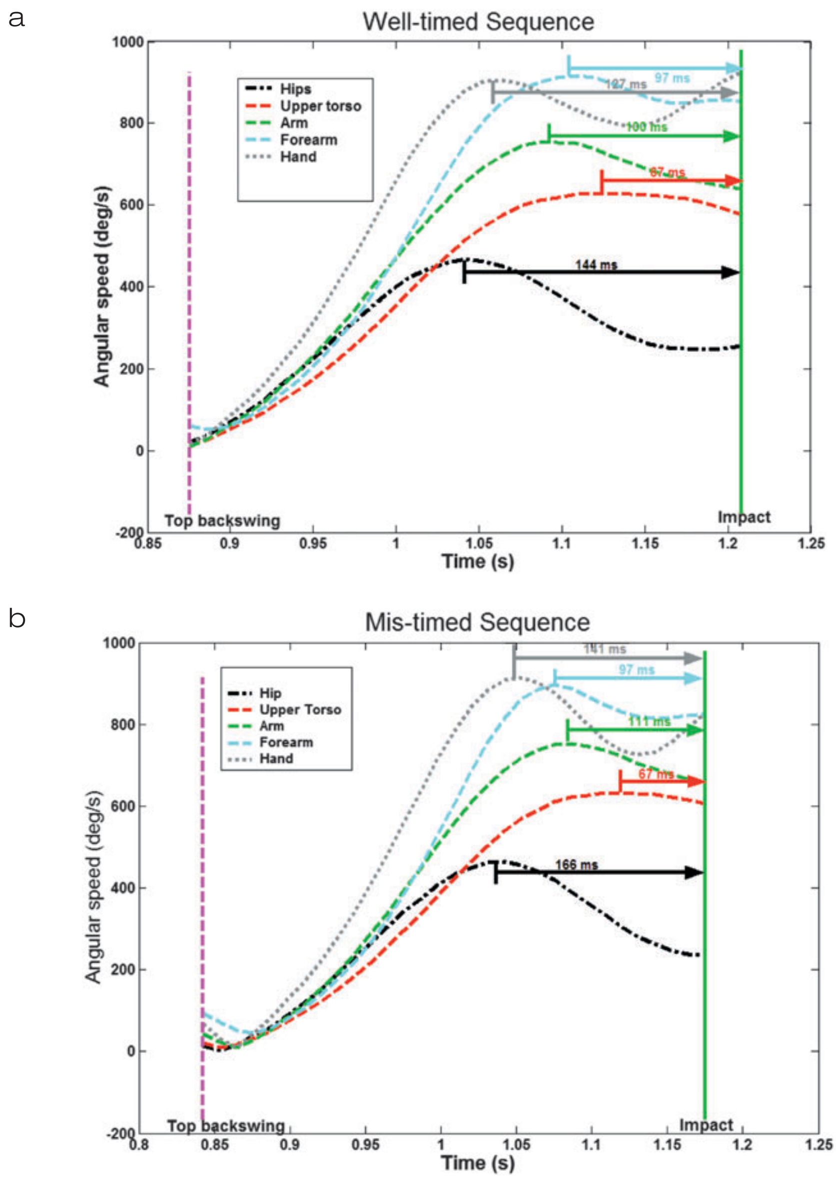

Figure 2. Examples of a Well-Timed Trial (a) and a Mistimed Trial (b) From One of the Subjects.

Note that the times of the hip peak speeds are substantially different as are the times of occurrence of the peak arm and hand speeds. The carry distances for the WT and MT shots were 297 m and 286 m respectively whereas the lateral errors were 0 m and 23 m respectively. The peak speed of the upper torso was 16 deg/s higher in the WT compared to the MT shot. Further, the linear speed of the hand was both higher (21 cm/s) and occurred closer to impact (11 ms) in the WT than the MT shot.

deviation, occurs nearly 100 ms earlier in the downswing than the peak axial rotation as the club face is squared up for impact.

We have alluded to a number of alterations to research design that would have allowed us improved insight into the notion of well-timed and mis-timed golf shots. The most poignant of these include the use of lesser-skilled subjects along with the highly skilled tour player or elite amateur player. We could then have presented data on poor timing as well as excellent timing in the creation of speed during the downswing. It would have been extremely useful to have had of the modern day launch monitors (e.g., Trackman) to accurately measure the club-ball impact, including pre-impact and post-impact velocity of the club head, ball spin and centeredness of contact.

CONCLUSION

Golf coaches need to develop a new and more complete understanding of the 'lags' that occur in the golf swing. Currently, the term 'lag' is used loosely to refer to delayed wrist uncocking. In other words, when golf coaches refer to 'lag' in a swing they are describing the phenomenon of maintaining a constant angle between the forearm and the club well into the downswing (i.e., not allowing this angle to increase too early). This study has revealed that there are distinct lags between the times of peak angular velocity of the different body segments and that these epochs are crucial for the efficient transfer of energy from the core of the body out to the periphery and the club.

There are some patterns of energy build-up in the body 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 this 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 lags between these peak speeds (see Table 4) that are indicative of a well-timed pattern of segment involvement in the action.

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 (i.e., proximal) 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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