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A three-dimensional examination of the planar nature of the golf swing

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Abstract

Previous planar models of the downswing in golf have suggested that upper limb segments (left shoulder girdle and left arm) move in a consistent fixed plane and that the clubhead also moves only in this plane. This study sought to examine these assumptions. Three-dimensional kinematic analysis of seven right-handed golfers of various abilities (handicap 0 – 15) was used to define a plane (named the left-arm plane) containing the 7th cervical vertebra, left shoulder and left wrist. We found that the angles of this plane to the reference horizontal z axis and target line axis (parallel to the reference x axis) were not consistent. The angle to the horizontal z axis varied from a mean of 133° (s = 1°) at the start of the downswing to 102° (s = 4°) at impact, suggesting a "steepening" of the left-arm plane. The angle of the plane to the target line changed from − 9° (s = 16°) to 5° (s = 15°) during the same period, showing anticlockwise (from above) rotation, although there was large inter-individual variation. The distance of the clubhead from the left-arm plane was 0.019 m (s = 0.280 m) at the start at the downswing and 0.291 m (s = 0.077 m) at impact, showing that the clubhead did not lie in the same plane as the body segments. We conclude that the left arm and shoulder girdle do not move in a consistent plane throughout the downswing, and that the clubhead does not move in this plane. Previous models of the downswing in golf may therefore be incorrect, and more complex (but realistic) simulations should be performed.

Keywords: *Golf, kinematics, model, swing plane*

Introduction

Mathematical modelling of the golf swing has been developed over a period of more than 30 years, from the original work by the Royal Society Golf Group (RSGG; Cochran & Stobbs, 1968) to the present (Sprigings & Mackenzie, 2002).

The study carried out by the RSGG was the first systematic research into mathematical and biomechanical aspects of golfing techniques. The golf swing was modelled as a planar two-link system, named the "double pendulum", in which the upper link consisted of the left arm pivoted at the fixed "hub" (between left shoulder and chest) and the lower segment was the club which rotated about the wrist. Cochran and Stobbs (1968) reported that elite golfers showed marked similarities to the "double pendulum" and that this model was an excellent mathematical analogue of the golf swing. However, Jorgensen (1970, 1994) improved the double pendulum model by allowing for horizontal and vertical (but not angular) acceleration of the "hub". Jorgensen's model showed improved fit with the swing of low-handicap golfers, and he concluded that translation of the "hub" played an important role in generating torque and thus clubhead speed. Campbell and Reid (1985) produced a three-segment planar model that incorporated trunk rotation (about the spine) in addition to shoulder and wrist action (Figure 1). They then used this model to perform optimization and maximization of driving performance.

Sprigings and Neal (2000) also used a planar three-segment model (Figure 2), but incorporated more realistic muscle dynamics to investigate optimal limb sequencing and delay times for maximal clubhead speed. The results showed that correctly timed wrist torques could produce gains in clubhead speed.

The major supposition of all of these previous models has been that golf is a planar activity with trunk rotation, arm swing and clubhead motion all remaining in the same plane throughout the downswing. Furthermore, it has also been assumed that this plane does not change its orientation during the downswing. However, these assumptions have not

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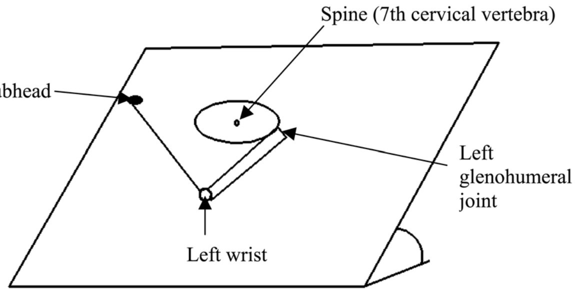

Figure 1. Three-segment model of the golf swing (adapted from Campbell and Reid. 1985)

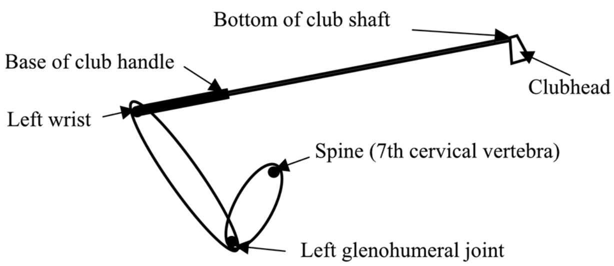

Figure 2. Three-segment model of the golf swing (adapted from Sprigings & Neal, 2000)

been empirically tested, although Vaughan (1981, p. 329) commented that "the plane of the shaft was *not* [original emphasis] constant", but also noted that 0.1 s before impact the plane "was fairly well established". Neal and Wilson (1985, p. 231) also stated in their conclusion that "the motion of the club was not planar for any substantial period of time during the downswing for any of the golfers", but did not give plane equations or state how far out of plane any of the digitized markers were.

Despite the remarks made in these two studies, golf is still assumed to be a planar action, with multi-segment planar models being recently published (Sprigings & Mackenzie, 2002). The aim of the present study was to provide more information on whether the downswing in golf was planar as specified in the models described above. These models assume that the shoulders, left arm and clubhead move in a fixed plane, so a planar anthropometric model containing the upper body and left arm was defined and named the "left-arm" plane. First, the consistency of orientation in space of this plane throughout the whole period of the downswing was examined. Second, the position of the clubhead relative to this plane was computed to determine whether the clubhead could be considered to be moving in the same plane as the upper body segments. These two sources of information were then used to test the assumption of a planar golf swing.

Methods

Participants

The participants were seven right-handed golfers with a mean age of 32.7 (s = 10.5) years, mean body mass of 80.5 (s = 4.3) kg and mean height of 1.81 (s = 0.03) m. They were selected from a range of handicaps to allow us to investigate whether players of various abilities fitted the planar model in different manners. Two golfers were professionals who played from "scratch" (handicap of 0) and five participants were club players (handicaps of 5, 8, 8, 12 and 15, respectively). Each golfer gave informed consent and then was filmed while performing golf swings with their own 5-iron clubs. Although participants in previous research have used drivers to hit the balls, 5-irons were chosen in the present study so that all golfers would be more likely to reproduce consistent shots. "Two-piece" golf balls were used for all shots.

Filming

The golfers executed shots on a sports field 250 m in length. The participants wore shorts and shoes, leaving their upper body naked. Five points (vertex of head, 7th cervical vertebra, left glenohumeral joint, left wrist, left third metacarpal–phalangeal joint) were identified on each golfer according to Plagenhoef (1971), as well as three on the club (base of handle, bottom of the club shaft and centre of clubhead) and the centre of the ball. Participants were allowed to warm up and practise for as long as they wanted and ten shots were then aimed on a specific target line but not to a particular point (due to the different clubhead velocities and maximum ranges generated by the individual golfers). The shots were qualitatively rated by the golfers and experimenters in terms of accuracy related to the target line, but not for distance (due to the different capabilities of the golfers).

Data collection and analysis

Two gen-locked Panasonic WVF-15 video cameras recorded the action at 50 fields per second with a shutter speed of 1/1000 s. The cameras were set at an angle of approximately 90° to each other and about 7 m from the players. The experimental set-up is shown in Figure 3. The performance space was defined by a 1.875 m cubed calibration frame (built by technical staff in the Physical Education, Sport and Leisure Studies Department at the University of Edinburgh) with 20 calibration markers of known location (to ± 1 mm), which was recorded before the swings of each golfer. As noted by Burden, Grimshaw and Wallace (1998), motion of the club occurs at high frequency through impact. However, as only

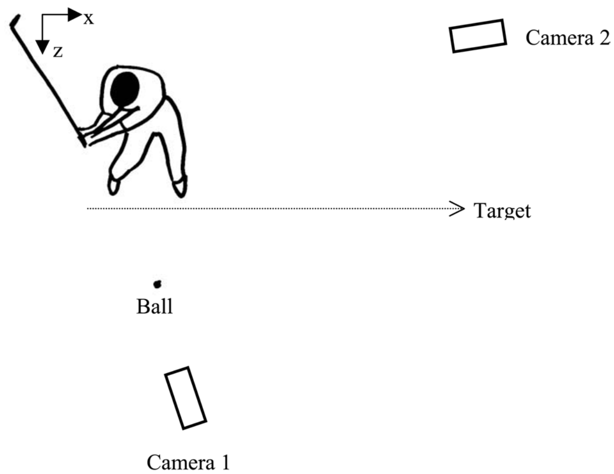

Figure 3. Experimental set-up

position data were used in the present study, and the fact that the limb motion takes place at lower frequencies, 50 fields per second was deemed appropriate. Also, only accurate (to target line) sequences in which the ball and clubhead appeared to be coincident at impact were used, so as to minimize clubhead position errors around ball contact. While 50 fields per second made the exact moment of impact difficult to assess, by using clubhead and ball velocities from previous literature (Sprigings & Neal, 2000), typical digitizing errors could be estimated. This resulted in timing errors of approximately 1.5 ms if ball and club appeared coincident on the video. As the time of impact in golf is 5 ms (Cochran & Stobbs, 1968), this was deemed acceptable. It was therefore possible to identify one sequence for each golfer in which ball and clubhead appeared coincident at impact and had been rated as being along the target line by golfer and experimenter.

Each sequence started at the first observed motion of the clubhead during the backswing and continued until ten fields after impact. Even though only the downswing (from reversal of clubhead direction at the top of the backswing until impact) was used for the planar analysis, this ensured that there were sufficient data before and after the period of interest for post-digitizing smoothing. The anatomical landmarks, club markers and ball were digitized in every field by the same operator using the Ariel Performance Analysis System running on a Viglen Contender 700 microcomputer with a 17 inch monitor. Three-dimensional object space coordinates were obtained from the 2 two-dimensional images using a direct linear transformation (Abdel-Aziz & Karara, 1971; Karara, 1980). Coordinates were then smoothed using a Butterworth fourth-order reverse filter with a cut-off frequency of 10 Hz for the body landmarks and 20 Hz for the club handle, bottom of the club shaft, clubhead centre and ball. These frequencies were chosen by visual inspection of the frequency spectrum for each point.

Three segments were defined. First, the left shoulder girdle segment was bounded by the 7th cervical vertebra and the left glenohumeral joint centre. Second, the left arm was defined as being between the left glenohumeral and left wrist joint centres. Finally, the club segment linked the left wrist joint centre and clubhead. The vertex and 3rd metacarpophalangeal joint were not included in any analysis, and were solely used to assist in identification of segments. The base of club handle and bottom of shaft markers were also not included in the subsequent planar equations, but were used solely for calculation of digitization accuracy (see below).

The equation of a plane was calculated by entering the three-dimensional coordinates of the 7th cervical vertebra, left glenohumeral and left wrist joints into a Microsoft Excel spreadsheet. This plane ("left-arm plane") containing the left shoulder girdle and left arm segments was given in the form $ax + by + cz + d = 0$, where a, b, c and d represent coefficients of the standard plane equation (Smyrl, 1978).

This plane was projected onto the yz and xz reference planes. The angles of these projections to the z reference axis (aligned on the ground at 90° to the target line) and the target line (parallel to the x axis) were then computed. The former gave the inclination of the left-arm plane to the horizontal (α), and the latter (β) provided information on the relationship of the left-arm plane to the target line (an angle of 0° showing that left-arm plane and target line were parallel). These angles are shown in Figures 4a and 4b. The consistency of these angles was then assessed by examining angle–time plots for the whole of the downswing phase. If the left-arm plane remained constant throughout this period as suggested in previous models, it would be expected that these two angles (α and β) would not change.

The perpendicular distance of the clubhead centre from the left-arm plane (Smyrl, 1978) was computed, giving an objective measure of whether the clubhead lay in the same plane, and therefore if the downswing could be considered planar as assumed by previous studies.

Digitizing accuracy was defined as the difference between known locations and reconstructed positions (Challis, 1997). This was determined in two ways. First, 16 known test points (independent of the control points) evenly distributed on the calibration frame were digitized for 10 fields and the root mean square error between object and unsmoothed image

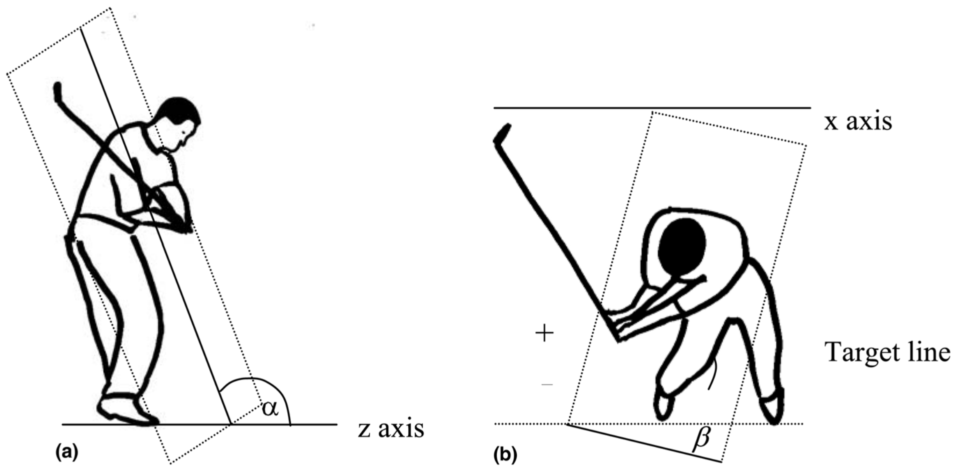

Figure 4a. Angel (α) of upper body and arm (left-arm) plane to Z Axis, showing club "below" plane. Figure 4b. Angle (β) of upper body and arm (left-arm) plane to target line (parallel to X axis). Position shown would result in a negative angle.

coordinates were calculated. Second, the calculated club shaft length (as defined as the distance between the unsmoothed digitized data for the club handle and the bottom of the club shaft) from one sequence of 60 fields was compared with a real measured value (to an accuracy of $\pm$ 1.0 mm) of club shaft length.

To estimate digitizing precision (Challis, 1997), one sequence was digitized six times and the unsmoothed data from each digitization were then used to calculate the left-arm plane. "Typical errors" (Hopkins, 2000) were calculated for the two plane angles and the clubhead distance, showing the precision of each of the computed variables. Typical error was used because it has been pointed out (Hopkins, 2000) that other measures, such as limits of agreement, are too large as a reference range for making a decision about a change in a participant's measurements.

Finally, coordinate data were also output to Virtual Reality Modelling Language files running on Cosmo Player software (Computer Associates, Islandia, NY, USA) to aid three-dimensional visualization of the left-arm plane, clubhead position and reference axes.

Results

Accuracy

The root mean square error of the 16 static test points were 7.1 mm, 9.8 mm and 5.1 mm for the x, y and z directions respectively, representing 0.4%, 0.5% and 0.3% of the calibrated volume. The mean club shaft length calculated from the digitized data was 687.5 (s = 19.4) mm, compared with a real measurement of 696 mm, giving a mean error of 8.5 mm (1.2%) and a root mean square error of 20.1 mm (2.9%).

Precision

Repeated digitization of one sequence gave typical errors of $\pm$ 4.1° and $\pm$ 2.8° for the angle between the left-arm plane and the z axis (α) and target line (β) respectively, and $\pm$ 0.07m for the clubhead distance from the left-arm plane. These represented 8.5%, 8.0% and 11.5% respectively of the range in these variables for the sequence digitized.

Angle of left-arm plane to horizontal (α)

The angle between the left-arm plane and the horizontal (z axis) is shown in Figure 5. Initial (top of backswing) angles were between 126° and 146° for the different players. All golfers then decreased the angle throughout the downswing, until at impact the mean angle was 102° (range 98–108°). This indicated that the left-arm plane "steepened" during the downswing. Four golfers continued to decrease their angle through impact, but participants 2 and 3 increased their angles slightly before impact. Player 5 showed a decrease throughout the latter half of his downswing, but then maintained a constant angle from 60 ms before impact until ball strike.

Angle of left-arm plane to target line (β)

The angle between the left-arm plane and the target line is shown in Figure 6, with a value of 0° indicating alignment between the left-arm plane and intended target line. Four of the golfers (participants 1, 4, 5 and 6) started the downswing with the left-arm plane aligned at an angle of greater than 0° (range 0–10°), indicating very slight anticlockwise (from above for a right-handed

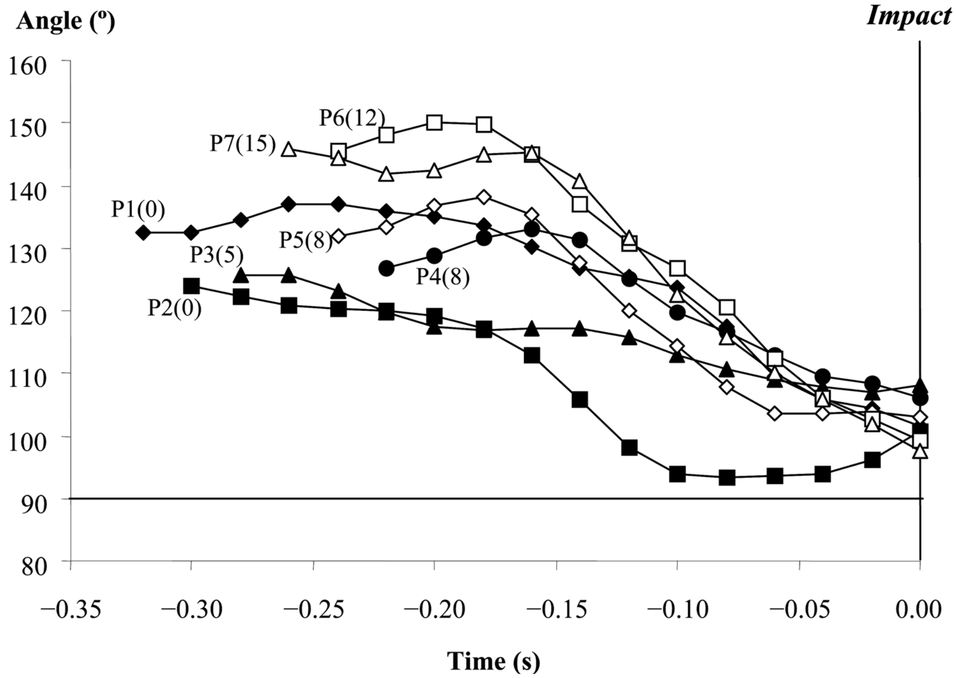

Figure 5. Angle (α) of upper body and arm (left-arm) plane to horizontal (Z axis) throughout downswing. Participant numbers are followed by handicap in brackets

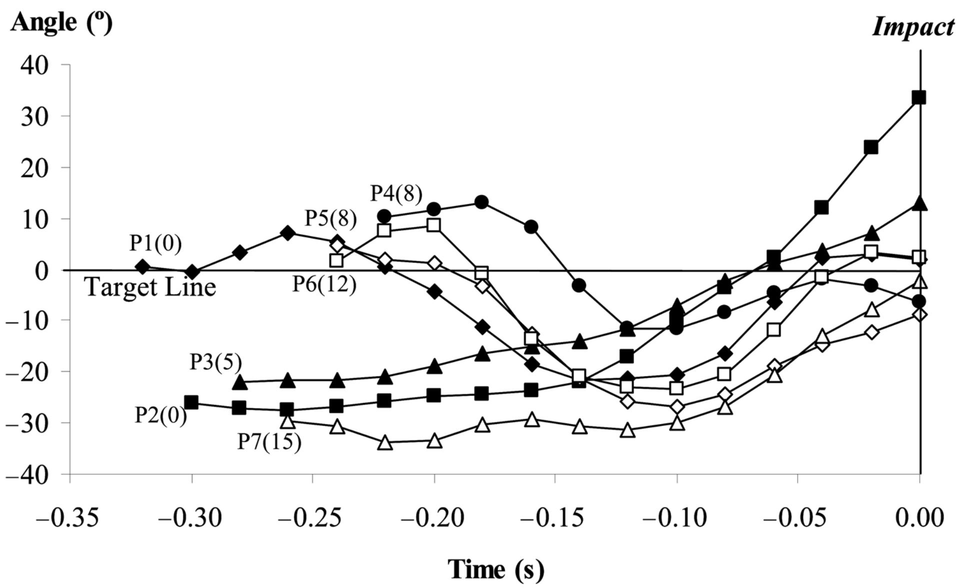

Figure 6. Angle (β) of upper body and arm (left-arm) plane to horizontal (X axis) throughout downswing. Participant numbers are followed by handicap in brackets

player) plane rotation past the target line. In all four cases, this was followed by a clockwise rotation of approximately 25° (range 22–34°) during the first half of the downswing. However, three golfers started with large negative left-arm plane to target line angles (clockwise) at the start of the downswing and a slight increase during the first half of the downswing. During the second half of the downswing (from approximately 100 ms before impact until ball contact), all participants increased the left-arm plane to target line angle (anticlockwise rotation). At impact, four golfers had obtained positive angles (rotation ‘‘past’’ the target line) of 2° to 33°, but the other three had not managed to rotate the left-arm plane to the target line (−9° to −2°).

Perpendicular distance of clubhead from left-arm plane

Figure 7 shows the perpendicular distance of the clubhead from the left-arm plane during the downswing. Negative values represent clubhead positions closer to the reference origin than the left-arm plane (i.e. the clubhead lies "inside" or "below" the plane), and positive distances show that the clubhead is further from the reference origin than the left-arm plane (i.e. the clubhead lies "outside" or "above" the plane). The participants did not show a constant distance from the left-arm plane throughout the downswing, but all increased the clubhead distance "outside" (positive) over the last 40 ms.

Discussion

The aim of this study was to determine whether a fixed plane formed by the 7th cervical vertebra, left glenohumeral and wrist joints (also known as the left-arm plane), as used in previous studies, was a realistic representation of the downswing phase in golf. Initially, the angles of this plane to the horizontal and target line were computed to determine whether it remained constant throughout the downswing. Examining Figures 5 and 6, it is clear that the left-arm plane was not consistent in either its horizontal or target line orientation.

All golfers decreased the angle of the left-arm plane to the horizontal throughout the downswing, thus "steepening" the swing. This can be seen as a logical consequence of left forearm supination in the latter part of the downswing (Cochran & Stobbs, 1968). If the left-arm plane did not "steepen", supination of the left forearm (and pronation of the right forearm) could not occur without the ball being missed. This action imparts extra speed to the clubhead (Cochran and Stobbs, 1968) as long as there is an angle between the club shaft and left-arm plane and this is the function of the "offset" angle of the club. This angle can be seen at address (Figure 8) and impact, although it varies for different golfers and different clubs, and is usually about 25–40°. Therefore, it is not possible or desirable to swing the club in the same plane as the left arm throughout the downswing.

The maximum rate of "steepening" of the left-arm plane of the individual golfers was fairly similar (although at different times in the downswing) apart from participant 3, who showed a much lower rate of decrease of left-arm plane angle to the horizontal. This player started the downswing with the second smallest angle and so it was not surprising that his rate of decrease was much lower than that of the other golfers. Participant 2, who started with the smallest angle, decreased the angle at approximately the same rate as all the other players early in the downswing. However, he maintained a constant angle 100 ms from impact and increased the angle 40 ms before impact, showing a slight "flattening" of the swing.

All golfers showed an increase in the angle of the left-arm plane to the target line during the latter half of the downswing, and this would be expected due to the anticlockwise rotation of the trunk and abduction (combined with horizontal extension and lateral

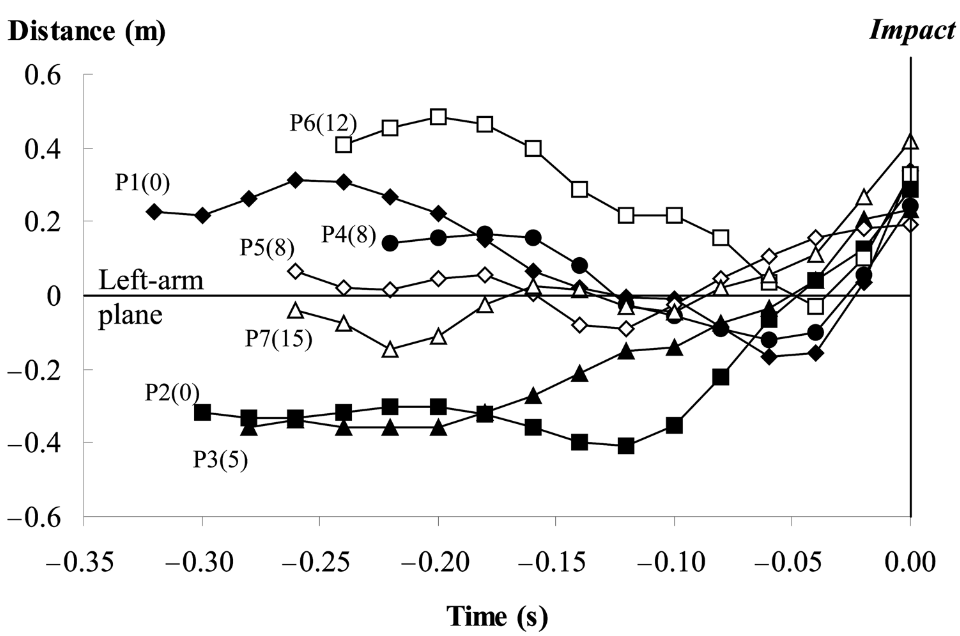

Figure 7. Perpendicular distance of clubhead from upper body and arm (left-arm) plane throughout the downswing. Participant numbers are followed by handicap in brackets

Figure 8. Address position showing "offset" angle between left-arm plane and clubshaft and distance from plane to clubhead

rotation) of the left arm. However, previous planar models (Campbell & Reid, 1985; Cochran & Stobbs, 1968; Sprigings & Neal, 2000) have ignored this factor, assuming the plane remains fixed in space through the downswing. As previously noted, four golfers rotated the left-arm plane past the target line (positive angles), whereas three did not achieve the target line. Participant 2 (handicap of 0) was again very different from the rest of the group, showing rotation of 33° past the target line, suggesting a large amount of trunk rotation and left arm abduction (and horizontal extension). Although not directly comparable with the left-arm plane analysis in the present study, Burden *et al.* (1998) did note that all but one of their participants rotated their shoulders past the target line, with the greatest value being 41°.

Given the complex rotation sequence of the golf downswing (including hip and shoulder rotation, left arm abduction and lateral rotation, left forearm supination, as well as adduction of the left wrist), it is perhaps not surprising that the movements of the shoulders and left arm do not remain in one consistent plane. In addition to the rotations incorporated in previous models, there is also translation of the centre of mass in three dimensions (Burden *et al.*, 1998), which makes the motion of the upper segments much more complex.

Figure 7 shows that the clubhead does not remain in the left-arm plane for any appreciable length of time, and that there are different techniques shown by the various players. It is difficult to draw conclusions regarding golfers' techniques from these data, as the success of any golf shot also depends on clubhead orientation and velocity vector at impact, and so clubhead position relative to left-arm plane may not be the most useful measure for shot effectiveness.

Figure 7 also confirms that there is an "offset" angle between the left-arm plane and the club shaft at impact, as all golfers displayed a clubhead position "outside" the body plane at ball contact. The distance of the clubhead from the plane varied from 0.19 m to 0.42 m; this distance depends on the length of the club, the size of the "offset" angle and also the "steepness" of the left-arm plane at impact. As stated previously, due to left forearm supination, it is not possible (or desirable) to have the clubhead in the same plane as the left arm and shoulders at impact.

This study utilized manual digitization of video film to generate image coordinates and to calculate subsequent (via direct linear transformation) object coordinates. Errors of digitization from this method are usually higher than those generated by automated marker tracking systems in laboratory conditions (Lindsay, 1996). In this study, root mean square errors of 5.1 – 9.8 mm were found for reconstruction accuracy of fixed test points in the 6.6 m^3 volume. These compare well with those previously reported by Challis (1995), who reported 6.1 – 23.0 mm for a 3.6 m^3 volume. However, accuracy of known club shaft lengths showed errors of 1.2% and 2.9% (mean and root mean square error), which are larger, as would be expected for an object moving three-dimensionally in space. These were extremely similar in magnitude to "external landmark" points (mean and maximum error of 1.3% and 2.7% respectively) in the study of Angulo and Dapena (1992). Precision, as shown by repeated digitization of one sequence, showed typical errors in the calculated variables of $\pm$ 8.5% (angle of left-arm plane to z axis), $\pm$ 8.0% (angle of left-arm plane to target line) and $\pm$ 11.5% (perpendicular distance of clubhead to left-arm plane).

Other studies using film or video to examine the kinematics of golf (e.g. Burden *et al.*, 1998; Vaughan, 1981) have not reported errors. However, it is accepted that the errors in the present study are larger than those reported for other activities using automated systems, in agreement with Lindsay (1996). The errors (particularly those in club length) compare well with the 28.5 – 49.4 mm (in an unspecified volume containing a discus circle) reported by Lindsay (1996) and a mean of 39 mm (with a calibration volume of approximately 5 m^3) reported by Angulo and Dapena (1992) for manual video digitization of external landmarks. However, it is recognized that the errors in the present study may negatively affect the accuracy of the results. Nevertheless, when comparing the magnitude of these errors with the values of the calculated variables, there is still enough evidence to support the facts that the left-arm plane does not remain consistent and that the clubhead does not remain in this plane throughout the downswing.

Conclusions

This study has shown that the left arm and club do not fit a fixed planar model during the downswing in golf, and so the assumptions used by previous studies using this type of model over the last 30 years may be erroneous. During the downswing, golfers do not move their left arm and left shoulder girdle in a consistent (left-arm) plane, and nor does the clubhead remain in this plane. We suggest that complex three-dimensional models of the golf swing that include variations in the left-arm plane and clubhead position should be developed to perform more realistic analyses in the future. These models will need to include more complicated mathematics that might be more difficult to solve or even indeterminate. However, to identify critical parameters in the golf swing, this degree of sophistication may well be required.

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