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ANALYSIS OF THE MOTION PLANES OF THE 'FUNCTIONAL DOUBLE-PENDULUM' POINTS IN GOLF

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The purpose of this study was to investigate the swing characteristics of the skilled and less skilled golfers by comparing the properties of the functional swing plane (FSP) and motion planes (MPs) formed by the clubhead and key functional double-pendulum points. Twenty-seven male golfers were recruited: skilled ($n = 15$; handicap ≤ 3) and less skilled ($n = 12$; 12-18 handicap). The slopes and direction angles of the FSP and MPs were quantified. The skilled group was characterized by steeper MPs than the less skilled ($p < 0.05$). The skilled group also revealed more closed (or less open) FSP and MPs than the less skilled with an exception: the left shoulder plane. The skilled group aligned the left hand plane with the FSP closely, whereas the less skilled group aligned the left shoulder plane with the FSP.

KEY WORDS: functional swing plane, trajectory-based, slope, direction, planarity.

INTRODUCTION: A golf swing is a complex 3D motion in which key body points such as the arm joints and the clubhead move on vastly different motion planes (MPs) (Kwon, Como, Han, Lee, & Singhal, 2012). While the entire downswing trajectory is not planar, the clubhead forms a clean 'functional swing plane (FSP)' during the execution phase (mid downswing to mid follow-through). The arm joints also form reasonably well-defined MPs but the slopes and directions of the MPs are vastly different from one another. The trajectory-based MP analysis approach provides with a means to highlight and analyse swing characteristics of the golfer.
In contrast to the original double-pendulum model (Cochran & Stobbs, 1968), Kwon et al. (2013) proposed the 'functional double-pendulum model' in which the moving hub is located in the mid-trunk area and the thorax, shoulder girdles, and arms collectively form the upper lever (with varying length). It is important to understand how the key functional double-pendulum points, such as the clubhead, arm joints (shoulder, elbow, and wrist), and the mid-trunk point move during the downswing. The purpose of this study was to investigate the swing characteristics of the skilled and less skilled golfers by comparing the properties of the FSP and MPs formed by the clubhead and key functional double-pendulum points.

METHODS: Twenty-seven healthy male golfers (all right-handed) were recruited and assigned to two skill groups: skilled (3 or lower handicap) and less skilled (12-18 handicap) (Table 1). The participant groups were not physically matched and the skilled group was significantly taller than the less skilled (Table 1).

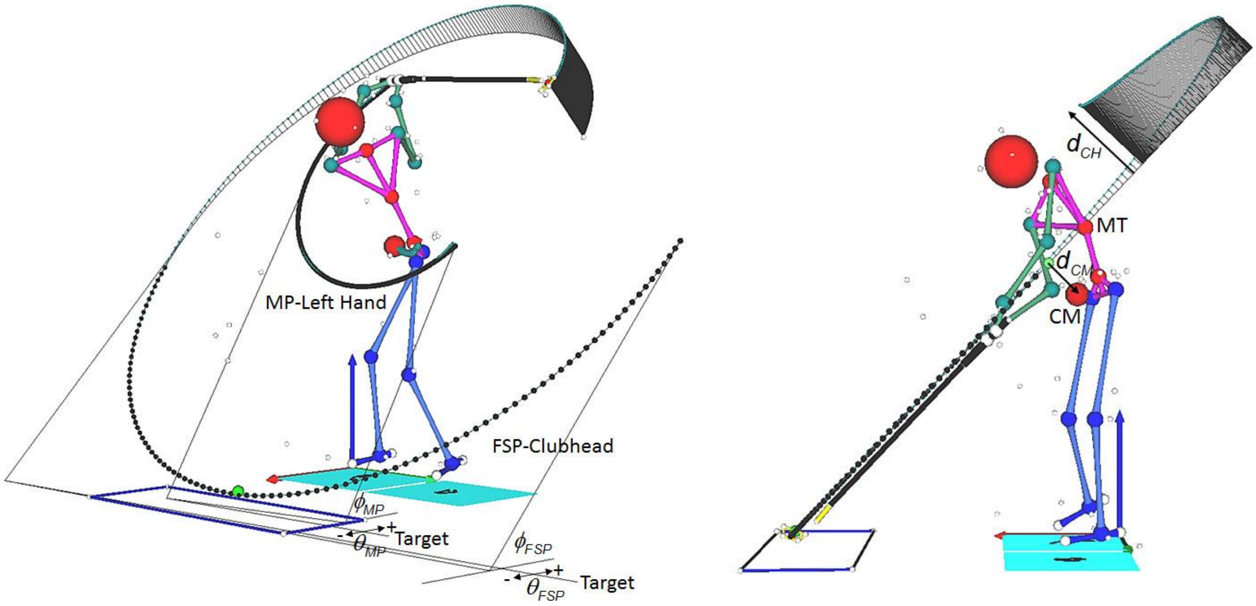
Table 1. Participant Characteristics

Variable	Skilled (n = 15)	Less Skilled (n = 12)
Mass (kg)	81.5 ± 9.6	86.3 ± 8.8
Height (cm)	182.6 ± 7.7	176.8 ± 4.4*
Handicap$^{\$}$	1.9 ± 1.8	15.3 ± 1.4*

$^{\$}$Plus handicaps were entered as negative numbers. *Significantly different from the skilled group ($p < 0.05$).

Each participant performed five successful driver trials using his own driver which were captured by a 10-camera Vicon Nexus real-time motion capture system (Vicon, Centennial, Colorado, USA; 250 Hz) and subsequently processed by Kwon3D XP Motion Analysis Suite (Visol, Seoul, Korea). The success of a shot was determined by shot direction, launch angle, and golfer's input in terms of solidness of the impact and body motion. Practice foam balls were used instead of real golf balls in the trials. The 'TWUGolfer2' body model with 63 markers, 31 secondary points (computed points including the joints), and 20 segments (including 5 trunk/shoulder segments) was used for the analysis. Zatsiorsky and Seluyanov's body segment parameters (ratios) corrected by De Leva (1996) were used in locating the CMs of the segments and the whole body.

To facilitate the analysis, a set of swing events were identified: TB (top of backswing), ED (early downswing), MD (mid downswing), BC (ball contact), and MF (mid follow-through) following Kwon et al. (2012). The plane fitting method outlined by Kwon et al. (2012) was used to locate the FSP formed by the clubhead (MD-MF) and the MPs of the functional double-pendulum points (mid-trunk, shoulder joints, elbow joints, and left hand; TB-MF). The slopes and directions of the FSP and MPs were computed (Figure 1A). To describe the position of the FSP relative to the golfer's body, the average deviations of the mid-trunk point (mid-point of xyphoid process and T12) and the whole body CM were also computed (TB-MF) (Figure 1B). The deviation of the clubhead from the FSP at TB was quantified as the initial position of the clubhead for the downswing.



(A) (B)

Figure 1. Variables computed: (A) plane angles of the functional swing plane (FSP) and an exemplar motion plane (MP-left hand), and (B) deviations of select points from the FSP. Slope (*ϕ*) and direction angle (*θ*) of each plane were computed. A positive direction angle means an open plane aligned toward the left side of the target line. The deviation (*d*) of the clubhead at TB and average deviations of the whole body CM and the mid-trunk point (MT) were computed.

A two-way repeated measure MANOVA was performed with 'Group' (between-subject; skilled and less skilled) and 'Point' (within-subject; clubhead, right shoulder, right elbow, right hand, left shoulder, and left elbow) factors. The dependent variables were slope and direction. A one-way MANOVA was conducted for the deviation parameters (clubhead deviation at TB and average deviations of the mid-trunk point and the whole body CM from the FSP during the downswing) with 'Group' factor. Post-hoc tests were conducted for significant factor effects and/or interactions. Alpha was set to 0.05 in all statistical operations. Huynh-Feldt adjustment was carried out to correct for violation of circularity, if any. Sidak correction was used for multiple comparisons. Due to the significant inter-group difference in height, Pearson's correlation coefficients were computed between the height and the slope/direction parameters of the FSP and MPs for each group (α = 0.05).

RESULTS: Significant Group*Point interaction (Wilk's λ = 0.173, F = 7.626, p < 0.001), Group effect (λ = 0.598, F = 8.060, p = 0.002), and Point effect (λ = 0.006, F = 257.176, p < 0.001) were observed for the slope and direction angles of the FSP and MPs. The group means and standard deviations along with the post-hoc analysis results are provided in Table 2.

Table 2. Summary of the Motion Plane Characteristics (in °)

Variable	Plane	Skilled (n = 15)		Less Skilled (n = 12)	
		M ± SD	Correlation[&]	M ± SD	Correlation[&]
Slope	FSP	48.3 ± 3.3	0.639*	49.4 ± 3.2	-0.458
	L. Shoulder	47.0 ± 5.4	0.264	41.1 ± 5.9[§]	0.010
	L. Elbow	50.6 ± 5.4	0.316	43.6 ± 6.7[§]	0.499
	L. Hand	57.9 ± 3.5	0.432	55.1 ± 4.3	0.159
	R. Shoulder	46.1 ± 6.2	0.370	37.3 ± 6.8[§]	-0.041
	R. Elbow	67.4 ± 7.1	0.529*	57.0 ± 10.4[§]	0.232
	Post-hoc	RE > LH > LE-FSP-LS-RS		RE > LH> FSP > LS-RS; RE > LH > LE	
Direction[$]	FSP	-3.8 ± 3.7	-0.262	0.4 ± 6.2[§]	-0.610*
	L. Shoulder	7.6 ± 9.3	-0.010	0.8 ± 7.2[§]	0.045
	L. Elbow	9.0 ± 6.4	0.095	15.7 ± 8.1[§]	-0.382
	L. Hand	-1.8 ± 5.5	-0.046	7.3 ± 8.1[§]	-0.644*
	R. Shoulder	-45.9 ± 15.3	-0.209	-39.3 ± 17.4	-0.094
	R. Elbow	-43.8 ± 9.0	0.000	-34.8 ± 5.8[§]	-0.647*
	Post-hoc	LE-LS > LH-FSP > RE-RS		LE > LH > FSP > RE-RS; LE > LS > RE-RS	

[$]A positive/negative angle means an open/closed plane aligned toward the left/right side of the target. [&]Correlation to body height. *Statistically significant correlation coefficient (p < 0.05). [§]Significantly different from the skilled group (p < 0.05). Abbreviations: FSP (functional swing plane), LS (left shoulder), LE (left elbow), LH (left hand), RS (right shoulder), and RE (right elbow).

The skilled group in general was characterized by steeper MPs of the arm points than the less skilled except the left hand plane (Table 2). The skilled group also revealed more closed (or less open) plane direction than the less skilled in the FSP and all MPs except the left and right shoulder planes. The left shoulder plane of the skilled group was significantly more open than that of the less skilled.

Among the points, the right elbow plane was the steepest, followed by the left hand plane (Table 2). In the skilled group, the slopes of the shoulder planes were similar to that of the FSP, whereas the less skilled group revealed significantly flatter shoulder planes than the FSP. In both groups, the right elbow and shoulder planes were identified as the most closed planes (negative direction angles) and left elbow plane as the most open plane (positive angle). Different trends were observed between the groups in terms of the direction angles of the left hand and left shoulder planes and the FSP.

The participant groups revealed substantially different correlation profiles between body height and plane properties (Table 2). Significant positive correlations to select slope parameters only (FSP and right elbow) were observed in the skilled group, whereas significant negative correlations to select direction angle parameters only (FSP, left hand, and right elbow) were observed in the less skilled group (Table 2).

Table 3. Deviations of the clubhead, mid-trunk point, and the whole body CM (in cm)[$]

Point	Skilled (n = 15)		Less Skilled (n = 12)	
	M ± SD	Correlation[&]	M ± SD	Correlation[&]
Clubhead (at TB)	23.2 ± 9.0	0.366	36.5 ± 17.5[§]	-0.125
Mid-Trunk (average)	0.0 ± 5.5	-0.302	-5.2 ± 7.1[§]	0.313
Whole body CM (average)	-15.1 ± 4.3	-0.230	-20.6 ± 6.6[§]	0.313

[$]A positive/negative value means the point is located above/below the functional swing plane. [&]Correlation to body height. [§]Significantly different from the skilled group (p < 0.05).

The skilled group was characterized by a smaller mean clubhead deviation from the FSP at TB (Table 3). The skilled group also showed relatively lower FSP position than the less skilled. The FSP was located near the mid-trunk point in the skilled group but passed above the mid-trunk point in the less skilled. No significant correlation to body height was observed in the deviation parameters regardless of the group (Table 3).

DISCUSSION: Considering the mean deviations of the mid-trunk point from the FSP (Table 3), it was deemed reasonable to use the mid-trunk point as the hub of the functional double-pendulum system (Kwon et al., 2013). The FSP was positioned closer to the whole body CM in the skilled group, meaning a shorter moment arm of the club reaction force (the force the club exerts to the hands). While the slopes were similar, the skilled group showed a more closed FSP (negative direction angle) aiming to the right side of the target.

Both groups showed similar slopes in the two most distal planes, the clubhead and left hand planes (Table 2). The skilled group, however, was characterized by steeper motion planes of the other points (elbows and shoulders). Among the MPs of the lead (left) arm points, the left hand plane was the steepest while the left shoulder plane was the flattest. The right elbow plane was steeper than the right shoulder plane. In terms of MP direction, the left elbow plane was identified as the most open plane (most positive mean direction angle) in both groups (Table 2). Different directional alignment strategies were observed: the skilled group aligned the left hand plane with the FSP closely, whereas the less skilled group aligned the left shoulder plane with the FSP. As a result, the left elbow and left shoulder planes were substantially open deviating from the FSP in the skilled group while the left elbow and left hand planes were substantially open in the less skilled group. Aligning the left hand plane with the FSP and along the target line (skilled group) was perceived as the superior alignment strategy. The less skilled group was characterized by a larger clubhead deviation from the FSP at TB (Table 3), suggesting a tendency of higher backswing and/or misalignment of the clubshaft with the direction of target at TB.

While the skilled group was significantly taller than the less skilled (Table 1), it was unlikely that the differences in the FSP position and MP alignment strategy were caused by the difference in the height when the inconsistent correlation profiles were considered (Tables 2 and 3). Nevertheless, a more thorough investigation on the effect of body size on FSP and MP characteristics with a larger sample size is warranted.

CONCLUSION: The purpose of this study was to investigate the swing characteristics of the skilled and less skilled golfers by comparing the properties of the FSP formed by the clubhead and the MPs of key functional double-pendulum points. The slope and direction angles of the FSP and MPs and the relative positions of the FSP to the mid-trunk point and whole body CM were compared between the skill groups. It was concluded that (1) the skilled group was characterized by steeper MPs than the less skilled; (2) the skilled group revealed more closed (or less open) FSP and MPs than the less skilled with one exception: the left shoulder plane; (3) the skilled group aligned the left hand plane with the FSP closely, whereas the less skilled group aligned the left shoulder plane with the FSP; (4) the FSP was located closer to the mid-trunk point and whole body CM in the skilled group than in the less skilled, resulting in a lower plane position in the skilled group.

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