Comparison of two- and three-dimensional methods for analysis of trunk kinematic variables in the golf swing

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ABSTRACT: Two-dimensional methods have been used to compute trunk kinematic variables (flexion/extension, lateral bend, axial rotation) and X-factor (difference in axial rotation between trunk and pelvis) during the golf swing. Recent X-factor studies advocated three-dimensional (3D) analysis due to the errors associated with two-dimensional (2D) methods, but this has not been investigated for all trunk kinematic variables. The purpose of this study was to compare trunk kinematic variables and X-factor calculated by 2D and 3D methods to examine how different approaches influenced their profiles during the swing. Trunk kinematic variables and X-factor were calculated for golfers from vectors projected onto the global laboratory planes and from 3D segment angles. Trunk kinematic variable profiles were similar in shape; however, there were statistically significant differences in trunk flexion (-6.5 ± 3.6º) at top of backswing and trunk right-side lateral bend (8.7 ± 2.9º) at impact. Differences between 2D and 3D X-factor (approximately 16º) could largely be explained by projection errors introduced to the 2D analysis through flexion and lateral bend of the trunk and pelvis segments. The results support the need to use a 3D method for kinematic data calculation in order to accurately analyse the golf swing

Introduction

The methods used to compute golfer kinematics during the golf swing have recently received increased attention in the biomechanics literature.[1–3] In particular, the suitability of using two-dimensional (2D) methods for computing golfer kinematics, specifically X-factor (defined as the relative axial rotation of the trunk and pelvis segments), has been questioned, and three-dimensional (3D) methods have been proposed to better represent the varying orientation (ie, flexion/extension, lateral bend, and axial rotation) of the trunk and pelvis throughout the golf swing.[2,3]

In the golf biomechanics literature, trunk flexion and lateral bend have typically been reported as 2D angles.[4,5] For right-handed golfers, 2D trunk flexion and trunk right-side lateral bend have been found to be important predictors of driving ball velocity.[5] A minimal change in golfers' 2D trunk flexion from top of the backswing to impact has been described as beneficial for allowing body and club rotations to remain on a plane.[5] Two-dimensional trunk right-side lateral bend increased from 40 milliseconds before impact to the time of impact,

which the authors described as upper body lag.[5] However, McTeigue et al[6] acknowledged the oversimplification of 2D interpretation of trunk flexion and suggested that maintaining constant lower trunk flexion could cause excessive movement in other directions (ie, lateral bend angles). Two-dimensional and 3D trunk flexion, lateral bend, and rotation angles have not been compared during the golf swing and could suffer from similar limitations to the recently critiqued X-factor computations.

Trunk axial rotation is a contributor to the much studied X- factor.[7] X-factor has been found to correlate with performance measures such as ball velocity[5,8] and clubhead linear velocity at impact[9]. Previous 2D approaches for computing X-factor have defined the angle between vectors representing the trunk and pelvis segments when projected onto the global horizontal plane[8,10] or functional swing plane.[3] In situations where these vectors do rotate in a plane parallel to the horizontal plane, then this simplification would be unlikely to introduce a significant error in X-factor values. However, in reality, the golfer's trunk and pelvis rotate about an inclined axis[5,6] and with 6 degrees of freedom; thus, projecting the trunk and pelvis vectors onto the global horizontal plane

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will introduce errors to the 2D X-factor calculation. Even projecting onto the functional swing plane, defined from the clubhead trajectory in the downswing[3] has limitations as this plane has been shown to vary throughout the downswing.[12]

Due to these limitations, 3D X-factor is suggested to provide a more accurate estimate of the difference in axial rotation between the golfer's trunk and pelvis during the golf swing.[1–3,13] Both Brown et al[2] and Kwon et al[3] compared the 2D projection methods (horizontal and swing plane projections) and relative 3D axial rotation of the trunk and pelvis for calculating X-factor. Larger X-factor was computed using the 2D projection method compared with 3D methods throughout the downswing and was attributed in part to the changing pelvis and trunk orientations (ie, flexion/extension, lateral bend, axial rotation) of individual golfers.[3] Nevertheless, neither study quantified the contribution of changing pelvis and trunk orientations to the difference in 2D and 3D X-factor or the improvement in accuracy gained by 3D analysis and thus it is unknown whether the additional complexity of a 3D analysis is necessary.

The purpose of this study was to compare trunk flexion, trunk lateral bend, trunk axial rotation, and X-factor calculated using 2D and 3D methods, in the general golfing population, to address 2 research questions. The first research question posed was how different are 2D and 3D trunk kinematic variables (flexion/extension, lateral bend, and axial rotation) at key instances (takeaway, top of the backswing, and impact) and throughout the swing? It was hypothesized that 2D trunk kinematic variables would be significantly greater than 3D trunk kinematic variables, in particular at top of the backswing and impact, as previous literature had shown for trunk axial rotation.[3,14]

The second research question posed was to what extent does a golfer's trunk and/or pelvis orientation, relative to the global coordinate system, account for the differences between 2D and 3D analyses of X-factor? Based on previous studies,[2,3] it was hypothesized that trunk and pelvis orientations would be significant predictors of the difference between 2D and 3D X-factor. The comparison between 2D and 3D methods may help interpretation of results from biomechanics literature regarding trunk kinematics and provide further evidence on whether a 3D analysis of the golfer kinematics during the golf swing is necessary.

Methods

Participants

Whole body kinematics were recorded for fifteen right-handed golfers (age 30 ± 10 years, mass 77.0 ± 11.9 kg, height 1.77 ± 0.07 m) of varying abilities (handicap range 1 - 29). All subjects gave their informed consent and ethical clearance was obtained from the University Ethical Advisory Committee.

Data collection

Fifty-five 14 mm diameter reflective markers were placed on the golfer at anatomical positions and five markers, including one wand marker, were placed on the golfer's own driver (Figure 1). A piece of reflective tape was placed on the golf ball enabling the instant of impact to be determined. Three-dimensional marker trajectories were collected using a thirteen camera Vicon Nexus Motion Analysis System (Oxford Metrics Ltd, UK) sampling at 250 Hz. The Vicon Nexus motion analysis system used in this study was capable of repeatedly measuring known distances and angles within 0.2 mm and less than 0.2° respectively throughout the capture volume which were measured using methods similar to Richards[15].
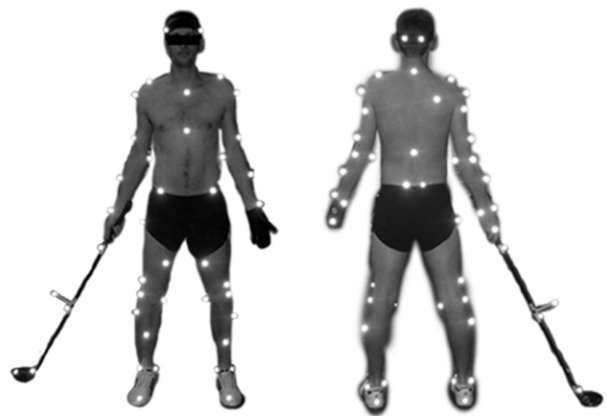

Figure 1. Marker set-up including seventh cervical vertebrae (C7), tenth thoracic vertebrae (T10), clavicle and sternum right and left; front and back head, acromion processes (RAC, LAC), shoulder (RSHO, LSHO), upper arm (three markers each), lateral and medial elbow epicondyles, forearm, medial and lateral wrist, hand, anterior and posterior superior iliac spine (RASI, LASI, RPSI, LPSI), thigh (three markers each), lateral and medial femoral epicondyle, shank (two markers each), lateral and medial malleoli, first metatarsal. Club markers include markers on the grip, shaft, heel and toe and a wand marker on the shaft.

Golfers wore their own golf shoes and glove, used the same brand golf ball (Titleist ProV1) throughout and hit from an artificial golf range mat into an indoor net positioned approximately four meters away; a vertical pole positioned behind the net provided a target line. The global co-ordinate system (GCS) origin (0,0,0) was at ground level in the middle of the capture volume. The positive GCS axes were defined from the origin, with the X-axis directed parallel to the target line but away from the target, the Y-axis directed anteriorly to the golfer and the Z-axis was directed vertically upwards.

Each golfer performed a warm up at their own discretion before testing began. The golfer then performed ten shots with their driver, with adequate rest between, based on the instruction to address the ball in their normal stance position and to hit a full shot aimed towards the target line. Following each shot, the golfer gave a subjective assessment of shot quality on a 10-point scale (1-10) where the highest rating was considered representative of their best shot.

Data analysis

Marker positions were labelled using Vicon Nexus (Oxford Metrics Ltd, UK) and further processing was done using Visual3D (C-Motion, USA). Marker trajectories were filtered using a fourth order zero-lag Butterworth low-pass filter with a cut-off frequency of 15 Hz. Five trials per golfer were selected for analysis based on the quality of data and a high subjective rating of shot quality, similar to the criteria proposed by Wheat et al.[13].

The methods used to calculate the variables trunk flexion, trunk lateral bend, trunk axial rotation and X-factor (trunk and pelvis) are summarized in Table 1. The 2D method involved projecting trunk and pelvis vectors onto the global sagittal plane (flexion), frontal plane (lateral bend) and horizontal plane (rotation and X-factor). For the 3D method a Cardan rotation order of YXZ was selected to give the most appropriate representation of trunk flexion, lateral bend and axial rotation throughout the golf swing as also noted by Joyce et al.[1]. Notably, all the methods were based on the same trials and marker positional data, but only differed in whether trunk kinematic variables or X-factor was determined from 3D segment angles or from their 2D projections onto the global planes. For 2D and 3D angles, positive angles represented trunk extension, trunk right-side lateral bend and axial rotation towards the target.

All kinematic data were cropped from takeaway to the mid follow-through, with top of the backswing and impact also identified. These key instances were defined using the following threshold functions: takeaway when the x-component of velocity of the clubhead heel marker first increased above 0.2 ms−1; top of the backswing when the x-component of velocity of the clubhead heel marker changed from negative to positive; impact as the frame where ball x-position first changed; and mid follow-through when the club shaft was parallel to the global x-axis following impact. The five cropped swings for each golfer were then time normalized in MATLAB (The Mathworks, Natick, MA) using the piecewise linear length normalization technique to align data from takeaway to top of the backswing, top of the backswing to impact, and impact to mid follow-through[16]. Ensemble averages for the entire group were calculated from the individual golfer averages.

Statistical Analysis

Statistical analysis was completed in MATLAB and SPSS v14 (IBM Inc., Armonk, NY). Mean difference, standard deviation of the difference, and 95% limits of agreement (LoA) were calculated for values at takeaway, top of the backswing, and impact for trunk extension, trunk right-side lateral bend, and trunk axial rotation to assess agreement between 2D and 3D methods. A positive mean difference signified greater trunk extension, greater right-side lateral bend, and greater trunk axial rotation when computed using 2D methods compared with 3D methods. A two-way repeated-measures ANOVA (2 × 3) was performed on each of the 3 dependent variables (trunk extension, trunk right-side lateral bend, and trunk axial rotation) between 2 methods (2D and 3D) and 3 swing instances (takeaway, top of the backswing, impact). If there was a significant interaction between method and swing instance, the effect of the method was analyzed for each swing instance using a one-way ANOVA. Normality and sphericity were checked and confirmed for all dependent variables and the significance level was set at $P < .05$. Ensemble average curves and mean difference curves of all trunk angles were visually analyzed for deviations between 2D and 3D methods.

To approximate the contributions of pelvis and trunk orientation to the difference in X-factor at top of the backswing calculated using 2D and 3D methods, a mixed-effects linear regression model was fitted to the difference between 2D and 3D X-factor (dependent variable) and the 3D pelvis and trunk extension, lateral bend, and axial rotation angles (6 explanatory variables). The golfer was treated as a random effect in the mixed-effects linear regression model to account for the 5 repeated trials for each golfer. A backward elimination method was employed whereby all explanatory variables were considered in the regression model and explanatory variables that did not contribute to the overall significance of the model (ie, $P < .05$) were removed in a stepwise manner and not considered in the adjusted R^2 value. X-factor values at top of the backswing were chosen as this was the swing instance often related to measures of performance such as ball velocity[5]

Results

The results from the comparison of 2D and 3D trunk kinematic variables helped answer question one and provided evidence regarding the first hypothesis. The general shapes of 2D and 3D trunk angles were similar when considering group ensemble averages (Figure 2a, c, e). However, 2D methods resulted in less trunk extension and less trunk axial rotation towards the target (i.e. greater negative mean difference) from TA to TB (Figure 2b, f) which helped answer the first research question and provided evidence regarding the first hypothesis.

The mean difference between 2D and 3D methods for trunk angles across all swing instances ranged from approximately 3° to -11° (Table 2). The two-way repeated measures ANOVA analysis confirmed that there was a significant interaction between methods (2D vs. 3D) and swing instances (TA, TB, IMP) for trunk extension ($F(2,28) = 29.38$, $P < .001$), trunk right-side lateral bend ($F(2,28) = 48.22$, $P < .001$) and trunk axial rotation ($F(2,28) = 15.86$, $P < .001$). Therefore, a comparison between 2D and 3D methods at each swing instance for each trunk angle was performed. At TA there were small non-significant mean differences between 2D and 3D trunk angles but there were statistical differences at TB and IMP. At TB, the 2D trunk flexion was significantly greater compared to 3D (-6.54 ± 3.64°, $P < .001$). At the same instance, 2D trunk axial rotation away from the target was greater than 3D (-10.97 ± 5.87°) which approached significance ($P = .068$) (Table 2). The Limits of Agreement at TB were wide across all trunk angles (-14 to -23°). At IMP, 2D

trunk right-side lateral bend angles was significantly less than the 3D angles ($P =.002$). At IMP, the Limits of Agreement were again wide across trunk angles (-4 to -22°).
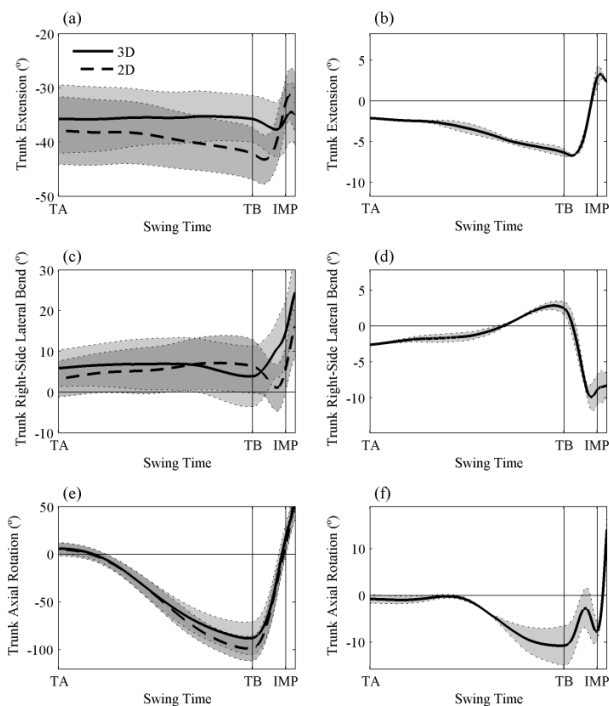

Figure 2 - 2D (dashed) and 3D (solid) ensemble average curves ± one standard deviation (shaded region) for (a) trunk extension, (c) trunk right-side lateral bend and (e) trunk axial rotation for all golfers and mean difference (2D – 3D) of (b) trunk extension, (d) trunk right-side lateral bend and (f) trunk axial rotation (towards target) for all golfers. A positive mean difference represented 2D methods had computed greater trunk extension, greater trunk right-side lateral bend and greater trunk axial rotation towards the target compared to 3D methods. TA = takeaway, TB = top of the backswing, IMP = impact.

Table 1 Summary of the methods used to calculate two- and three-dimensional trunk flexion, lateral bend, rotation and X-factor.

Parameter	2D Definition	2D Angle	3D Definition	3D Angle
Trunk Extension	Vector between C7 and Mid-PSIS markers.	Vector projected onto GCS sagittal plane and vector measured relative to vertical Z-axis	Origin: Mid-acromion and halfway to T10 x-axis: z-axis to right acromion y-axis: cross product of x and z-axis z-axis: Origin to mid acromion	Rotation about GCS frontal horizontal axis (X-axis).
Trunk Lateral Bend	Vector between C7 and Mid-PSIS markers.	Vector projected onto GCS frontal plane and vector measured relative to vertical Z-axis		Rotation about GCS sagittal horizontal axis (Y-axis).
Trunk Axial Rotation	Vector between right and left acromion markers.	Vector projected onto GCS horizontal plane and vector measured relative to Y-axis		Rotation about GCS vertical axis (Z-axis).
X-Factor (Trunk and Pelvis)	Trunk: Vector between right and left acromion markers. Pelvis: Vector between right and left ASIS markers.	Vectors projected onto GCS horizontal plane. X-factor is the angle between projected vectors.	Trunk defined as above. Pelvis Origin: Mid-ASIS markers x-axis Origin to right ASIS marker y-axis Cross product of x and z axis z-axis: Cross product of x-axis and unit vector from origin to mid-PSIS	Axial rotation angle between trunk and pelvis segments.

Table 2 Mean difference, standard deviation of the difference (SD), 95% Limits of Agreement (LoA) and *P* values for mean 2D and 3D trunk flexion, lateral bend and axial rotation at takeaway (TA), top of backswing (TB) and impact (IMP). A negative mean difference signifies that 2D angles were greater than 3D angles and vice versa.

Key Instance	Angle	2D – 3D Trunk Angles (º)			
		Mean Difference	SD	95% LoA	*P*
TA	Trunk Extension	-2.12	3.01	3.78	-8.03	.370
TB		-6.54	3.64	0.59	-13.67	.001**
IMP		3.03	3.57	10.03	-3.98	.117
TA	Trunk Right-side Lateral Bend	-2.61	2.67	2.62	-7.85	.122
TB		2.45	2.99	8.31	-3.41	.354
IMP		-8.65	2.91	-2.95	-14.36	.002**
TA	Trunk Axial Rotation	-0.77	5.33	9.69	-11.22	.750
TB		-10.97	5.89	0.57	-22.52	.068
IMP		-7.27	7.37	7.17	-21.72	.138

** *P* < .01

Table 3 Mean ± SD angles at TB of predictor variables and standardised beta coefficients (β-coefficient), standard error (SE) and *P* values from the stepwise mixed effects regression model.

Variable	Mean ± SD (º)	β-coefficient	SE	*P*
Pelvis Extension	-18.26 ± 5.85	0.19	0.12	.109
Trunk Extension	-35.61 ± 4.69	0.06	0.08	.479
Pelvis Right-side Lateral Bend	-4.59 ± 5.26	0.20	0.10	.053*
Trunk Right-side Lateral Bend	3.86 ± 7.48	-0.53	0.10	.001**
Pelvis Axial Rotation	-44.82 ± 10.94	0.41	0.13	.003**
Trunk Axial Rotation	-87.10 ± 17.78	-1.06	0.13	.001**

** *P* < .01, * borderline *P* < .05

When comparing trunk angles for individual golfers, greater differences were observed in the patterns between 2D and 3D curves. To illustrate these differences, two golfers with the greatest (Golfer One, handicap = 9) and least (Golfer Two, handicap = 2) difference in 2D – 3D trunk axial rotation at TB were used as examples (Figure 3). Golfer One exhibited a greater change in 3D trunk extension throughout the swing with the golfer becoming more flexed towards TB compared to TA (Figure 3a). Two-dimensional trunk extension follows a similar pattern to the 3D pattern but appeared to report a greater amount of trunk flexion compared to 3D angles (Figure 3a). The greater difference in magnitude between 2D and 3D trunk axial rotation curves, from TA to TB, can also be observed for Golfer One (Figure 3e). For Golfer Two, 2D trunk flexion increases towards TB, whilst 3D trunk flexion remained relatively stable (Figure 3b). For the same golfer, in the late backswing, 3D trunk right-side lateral bend increased before TB and continued to rapidly increase during the downswing (TB – IMP) which may be seen as increased trunk flexion when reporting 2D angles (Figure 3d). Nevertheless, the 2D and 3D trunk rotation curves remained similar in pattern and magnitudes (Figure 3f).
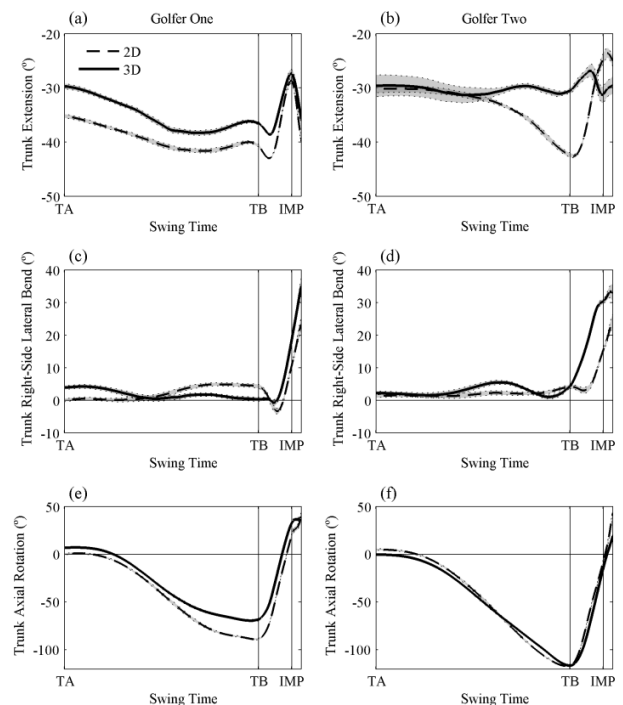
Figure 3 - Individual golfer mean curves ± one SD (shaded region) of 2D (dash) and 3D (solid) trunk kinematics for (a,c,e) Golfer One (greatest difference in axial rotation at TB) and (b,d,f) Golfer Two (smallest difference in axial rotation at TB).
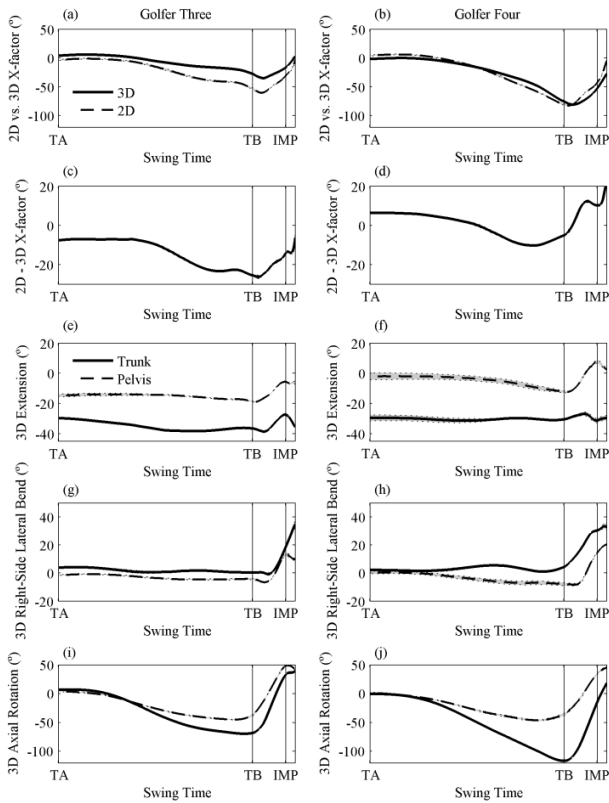
Figure 4 - Mean ± standard deviation (solid line and shaded region respectively) of (a,b) 2D vs. 3D X-factor, (c,d) X-factor mean difference (2D – 3D), (e,f) 3D pelvis and trunk extension, (g,h) 3D pelvis and trunk lateral bend (i,j) 3D pelvis and trunk axial rotation for Golfer Three and Four (greatest and least difference between 2D and 3D X-factor at TB respectively). A positive mean difference represented 2D methods computed greater trunk extension, greater trunk right-side lateral bend and greater trunk axial rotation towards the target compared to 3D methods.

Figure 5 – Front, side and top view of golfer models with pelvis (black) and trunk (grey) vectors with projection onto the GCS horizontal plane at TB for Golfer Three and Golfer Four

From the regression analysis, of the six predictor variables, three (trunk right-side lateral bend, pelvis and trunk axial rotation) were significant and contributed to the adjusted R^2 value of 0.967 (Table 3). Across all golfers, the mean difference and standard deviation between 2D – 3D X-factor at top of the backswing was -16.72 ± 6.20º. Of these explanatory variables, the most important predictor of the difference between 2D – 3D X-factor was trunk axial rotation (β = -1.06) followed by trunk right-side lateral bend (β = -0.53) and pelvis axial rotation (β = 0.41). The negative β-coefficients for trunk axial rotation and trunk right-side lateral bend indicated that as these variables increased by one standard deviation (i.e. less rotation away from target and greater trunk right-side lateral bend) the difference between 2D – 3D X-factor at TB would increase by approximately 6.6° and 3.3° respectively. An increase of one standard deviation in pelvis axial rotation would reduce the difference in 2D – 3D X-factor at TB (approximately 2.5°).

To further explore the results of the regression analysis two individual golfers, one with the greatest difference in 2D – 3D X-factor at TB (Golfer Three, handicap = 9, difference ~ -25°) and one with the smallest difference in 2D – 3D X-factor at TB (Golfer Four, handicap = 2, difference ~ -5°) were selected (Figure 4 and Figure 5). In terms of the significant predictor variables that emerged from the regression analysis, the major difference between golfers was in trunk axial rotation where Golfer Three had markedly less trunk axial rotation away from the target line compared to Golfer Four (70° versus 110° at TB; Figures 4i–j and 5). In comparison, trunk right-side lateral bend (Figures 4g–h and 5) and pelvis axial rotation (Figures 4i–j and 5) were both very similar between the two golfers. Thus, it appears that it was the relatively small trunk axial rotation away from the target line that was the major contributor to the large difference between 2D and 3D X-factor for Golfer Three.

Discussion

This study compared trunk kinematics (flexion/extension, lateral bend, axial rotation) and X-factor during the golf swing using both 2D and 3D calculation methods of the same kinematic data in the general golfing population. Two-dimensional trunk flexion was significantly greater (approximately 7°) than 3D trunk flexion at top of the backswing and 2D trunk right-side lateral bend was significantly less than 3D trunk right-side lateral bend at impact. The 2D trunk axial rotation away from the target was also greater (approximately 11°) than 3D trunk axial rotation, although not statistically significant. These results support the first hypothesis that 2D trunk kinematic variables would be greater than 3D for 2 out of the 3 variables. The differences between 2D and 3D trunk kinematic variables became more evident when examining individual golfers, especially for a single golfer who exhibited greater trunk right-side lateral bend. The degree of 3D trunk axial rotation, trunk right-side lateral bend, and pelvis axial rotation were significant explanatory variables for the differences between 2D and 3D X-factor at top of the backswing. The result of the regression analysis supports the second hypothesis that trunk and pelvis orientations
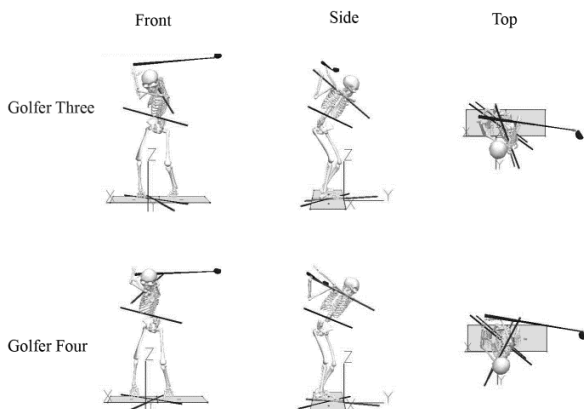
could explain differences between 2D and 3D X-factor, particularly at top of the backswing.

The shapes of the 2D and 3D trunk kinematics ensemble average curves were similar, but often varied in magnitude. Alkjaer et al [17] identified increased magnitude of 2D joint moments compared with 3D joint moments at specific events during gait. However, the patterns between data curves were very similar and, as a result, the authors concluded that 2D methods were appropriate to use for quantifying joint moments. A similar conclusion does not appear valid in this case for the golf swing as 2D and 3D calculation methods produced differences in trunk kinematic ensemble average curves which were shown to be significant at certain key swing instances such as top of the backswing and impact, although less so at takeaway. The increased differences at top of the backswing compared with takeaway could be due to the coupled movement of flexion/extension and lateral bend in the trunk that are not accounted for by 2D angles. Biomechanical coupling is a 3D concept where movement in a single direction, particularly for the trunk, can produce movement in other directions.[18] It has been identified that 2D measurement methods used in studies exploring coupling movements leads to magnification of errors in the measurement of segment angles and subsequently misleading results.[18] Interestingly, coupling patterns have been shown to vary between individuals,[19] further strengthening the need for 3D analysis and offering an explanation for the varying level of agreement between 2D and 3D analysis of trunk kinematics for individual golfers found in this study (Figure 3). Similarly, the large range between the upper and lower LoA at all key swing instances (Table 2) suggests that these differences could be quite variable between golfers. Relationships to performance measures (clubhead velocity, ball velocity) have mostly been found for 2D measures of trunk flexion, trunk right-side lateral bend, and X-factor.[5] Kwon et al,[3] however, recently reported a lack of significant correlations between 3D X-factor and clubhead velocity at several stages in the swing, and warned that significant correlations between 2D X-factor and ball/clubhead velocity[5] should be interpreted with caution. Kwon et al[3] suggested that fundamental differences in swing style (described as slope of swing plane, shape of clubhead trajectory) could influence both X-factor and clubhead velocity. These concerns are also relevant for previous significant relationships between 2D

There were also evident differences in X-factor calculated using the 2D versus 3D methods for individual golfers (Figure 4). Overall, the group mean 2D X-factor at top of the backswing showed increased rotation away from the target (by approximately 16°) compared with 3D X-factor. Kwon et al[20] reported that, at top of the backswing, 2D X-factor was approximately 3° greater than 3D X-factor, which was consistent with the trend observed in this study. However, Brown et al2 reported 3D X-factor to be greater than 2D X-factor at top of the backswing, by approximately 0.4° (standard error = 0.2°). The relatively small differences between 2D and 3D X-factor found in previous studies, compared with this study, could be due to the homogenous groups of golfers that the previous studies have used. The subjects recruited for this study intentionally included a wide range of ages (19–55) and handicaps (1–29) to obtain a wide range of trunk kinematics and X-factor values so that potentially more noticeable effects could be seen between 2D and 3D methods. This study was also able to show individual variations in the level of agreement between methods, which was a concerning factor for Brown et al.[2] Brown et al[2] noted that the difference between 2D and 3D X-factor varied between golfers and the mean difference did not reflect these individual golfer variations. Accurate estimation of X-factor at key instances, such as top of the backswing, is important in the analysis of the golf swing given that they have been shown to correlate with ball velocity[5] and to have a suitable range of values for regression analysis. Parameters such as X-factor stretch rely on quantification of X-factor at top of the backswing and maximum values and hence the methods used could affect the outcome. Furthermore, determining accurate timings of when maximum values occur during the swing may also be important to the performance outcomes of the swing (eg, ball distance and accuracy). For example, Tinmark et al[21] found that the timing of pelvis, torso, and hand segment velocities showed a proximal-to-distal sequencing, which was suggested to affect shot accuracy. The differences between X-factor values obtained from 2D versus 3D methods at top of the backswing resulted primarily from the associated movements of lateral bend and axial rotation of the trunk and pelvis segments during the golf swing. Stepwise regression analysis suggested that both pelvis and trunk kinematic variables accounted for approximately 96% of the explained variance between 2D and 3D X-factor calculation methods at top of the backswing (Table 3). The regression analysis suggested that golfers exhibiting lesser pelvis axial rotation away from the target would reduce the difference between 2D and 3D X-factor at top of the backswing. Conversely, golfers that had more trunk right-side lateral bend and lesser trunk axial rotation away from the target at top of the backswing would increase the difference between 2D and 3D X-factor at top of the backswing. This finding was supported by the example of the 2 golfers in Figure 4 and Figure 5. As mentioned previously, Kwon et al[3] suggested that X-factor and clubhead velocity could be influenced by fundamental swing style differences which could have contributed to the significant correlations observed between 2D X-factor and clubhead velocity in other studies.[5,8] The results of this study have shown that the X-factor measurement methods alone could be affected by changes in golfer's body movements in other planes (ie, trunk axial rotation and trunk right-side lateral bend) and therefore it is plausible that the 2D X-factor masks these additional golfer movements and the 2D X-factor would not be a suitable variable to correlate with measures of performance. Given the findings of this study and Kwon and colleagues'[3] study that significant and technique-dependent differences between 2D and 3D X-factor occur during the golf swing, the results of previous studies reporting significant correlation between X-factor and ball velocity based on 2D measurement of the former should be treated with caution. The results of this study serve to promote a consistent approach for quantifying X-factor and trunk kinematic variables using 3D techniques which will ultimately help to understand whether there is a correlation between these variables and measures of performance such as ball velocity.

In conclusion, this study has calculated and compared trunk kinematics (flexion, lateral bend, rotation) and X-factor during the golf swing using both 2D and 3D analysis of the same kinematic data. The 2D methods led to significant differences in trunk extension at top of the backswing and trunk

right-side lateral bend at impact. The degree of similarity between 2D and 3D trunk kinematics was highly dependent on the individual golfer's technique. The differences between 2D and 3D X-factor at top of the backswing were largely due to trunk extension, trunk axial rotation, pelvis axial rotation, and trunk right-side lateral bend. Once again, the degree of similarity between 2D and 3D X-factor were dependent on an individual golfer's technique. The primary source of differences appears to be associated with projecting vectors representing the trunk and pelvis onto a global plane throughout a 6 degree of freedom movement. Therefore, a golfer who has a greater degree of trunk flexion, trunk right-side lateral bend, or smaller degree of pelvis and trunk axial rotations may be susceptible to greater differences between 2D and 3D methods. These results support the need to use 3D methods for analyzing a golfer's trunk or pelvis segment kinematics during the full golf swing. The results of this study also have implications for golf coaches, specifically in their use of 2D videography to assess a golfer's swing. Clearly, interpretation of these videos needs to be treated with caution, particularly with respect to assessing the rotational movements of the golfer's trunk and pelvis.

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