Comparison of centre of gravity and centre of pressure patterns inthe golf swing

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ABSTRACT: Analysing the centre of pressure (COP) and centre of gravity (COG) could reveal stabilising strategies used by golfers throughout the golf swing. This study identified and compared golfers' COP and COG patterns throughout the golf swing in medial–lateral (ML) and anterior–posterior (AP) directions using principal component analysis (PCA) and examined their relationship to clubhead velocity. Three-dimensional marker trajectories were collected using Vicon motion analysis and force plate data from two Kistler force plates for 22 low-handicap golfers during drives. Golfers' COG and COP were expressed as a percentage distance between their feet. PCA was performed on COG and COP in ML and AP directions. Relationships between principal component (PC) scores were examined using Pearson correlation and regression analysis used to examine the relationship with clubhead velocity. ML COP movements varied in magnitude (PC1), rate of change and timing (PC2 and PC3). The COP and COG PC1 scores were strongly correlated in both directions (ML: $r = 0.90$, $P < .05$; AP: $r = 0.81$, $P < .05$). Clubhead velocity, explained by three PCs (74%), related to timing and rate of change in COP_{ML} near downswing (PC2 and PC3) and timing of COG_{ML} late backswing (PC2). The relationship between COP_{ML} and COG_{ML} PC1 scores identified extremes of COP and COG patterns in golfers and could indicate a golfer's dynamic balance. Golfers with earlier movement of COP to the front foot (PC2) and rate of change (PC3) patterns in ML COP, prior to the downswing, may be more likely to generate higher clubhead velocity.

Introduction

Maintaining a balanced body position is critical in-static (e.g. standing) and dynamic situations (e.g. walking) to prevent falling, achieve the desired posture or movement (Hsue, Miller, & Su, 2009; Winter, 1995). Golf coaches perceive golfers should remain balanced throughout the swing in order to maintain posture and produce accurate and powerful swings (Smith, Roberts, Wallace, Wah Kong, & Forrester, 2015). In the golf biomechanics literature, a balanced body position has not been fully investigated but studying centre of pressure (COP) and centre of gravity (COG) could reveal stabilising strategies used by golfers to remain balanced throughout the swing. Whole body COG position in the global horizontal plane (Winter, 1995) has been used as a measure of overall body movement during balance studies (Caron, Gelat, Rougier, & Blanch, 2000). COP position has been used as an indicator of the overall neuromuscular response to control the passive COG and restore equilibrium (Winter, 1995). The relationship between COG and COP revealed strategies for maintaining an upright posture during standing (Caron et al., 2000; Winter, 1995). In dynamic situations, the same strategy may not be indicative of instability and hence both measures should be investigated when analysing dynamic balance (Hsue et al., 2009). In this study, dynamic balance during the golf swing is explored by measuring COG and COP and is defined as a golfer's ability to remain balanced (i.e. not fall) whilst still achieving the intended outcome (i.e. generate high clubhead speed when striking the golf ball).

In the golf literature, more is known about COP patterns than COG (Ball & Best, 2007a, 2007b, 2012; Barrentine, Fleisig, & Johnson, 1994; Wallace, Grimshaw, & Ashford, 1994). Group- based analyses have revealed two styles of COP movement in the medial–lateral (ML) direction for a heterogeneous group of golfers (Ball & Best, 2007a, 2007b). The styles were termed "front foot" and "reverse foot" (Ball & Best, 2007a, 2007b). For both styles, COP moves to the back foot

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(defined as the right foot of a right-handed golfer) during the backswing. The front foot style was characterised by COP translating towards the front foot (defined as the left foot for a right-handed golfer) during the downswing and through impact. The reverse group started moving forward in the early downswing before positioning the COP towards the back foot in the downswing, with COP positioned close to mid-stance at impact. There were no statistically significant differences in handicap or clubhead velocity when comparing the two styles. More recently, however, Ball and Best (2012) found significant relationships between COP measures and clubhead velocity on an individual golfer basis. Individualised golfer relationships between COP parameters and measures of performance could be due to the use of discrete measures which may not adequately represent the key features of the COP time-series. In addition, previous golf biomechanics research has defined discrete events in different ways, such as top of the backswing, making it difficult to compare across studies (Smith et al., 2015). Continuous data analysis techniques, such as principal component analysis (PCA), could overcome these limitations by identifying the key features of COP trajectories across the whole time-series. The PCA technique has been used to identify unique biomechanical movement strategies in sporting movements within groups of similar (Donà, Preatoni, Cobelli, Rodano, & Harrison, 2009) and differing (Lynn, Noffal, Wu, & Vandervoort, 2012) ability sportsmen.

Studies by Ball and Best (2007a, 2007b, 2012) used COP to investigate the coaching term "weight transfer". However, strictly COG rather than COP describes how a golfer's weight is distributed throughout the swing (Jenkins, 2008). The term "weight transfer" is often used by coaches to describe the observed weight under each foot of a golfer and does not serve as a biomechanical description. ML COG movement patterns were shown to be similar across all ability right-handed golfers in the backswing of a golf drive (Burden, Grimshaw, & Wallace, 1998). During the downswing, differences in ML COG motion were observed and more linear patterns were associated with improved performance yet no direct comparisons were made to COP or measures of performance (Wrobel, Marclay, & Najafi, 2012). Choi, Kang, and Mun (2016) furthered this finding by reporting that COG and COP separation could distinguish between golfing abilities and provided a valuable quantitative measure of a golfer's dynamic balance. Nevertheless, the study made no reference to individual golfer differences, analysed COG–COP during three distinct swing phases and also had no measure of performance.

The purpose of this study was to identify and compare golfers' COP and COG movement patterns throughout the golf swing in ML and anterior– posterior (AP) directions using PCA and identify relationships with measures of performance. The results could highlight different strategies employed by golfers to achieve dynamic balance during the golf swing and identify the key features of COP and COG movement patterns related to performance.

Methods

Participants

Twenty-two right-handed low-handicap golfers (handicap range + 3 to 4; age = 26 ± 7 years; height 179.5 ± 7.3 cm; mass = 79.4 ± 13.1 kg) were recruited for the study. Golfers were either members of the University golf team or professional golfers from local clubs. All golfers gave their informed consent and ethical clearance was obtained from the University Ethical Advisory Committee.

Data collection

Testing took place in an indoor laboratory and three-dimensional marker trajectories were collected using the Vicon Nexus Motion Analysis System (Oxford Metrics Ltd, UK) sampling at 250 Hz. Sixty-three, 14 mm diameter retro-reflective markers were placed on each golfer at anatomical locations and four markers were placed on the golfer's own driver (Appendix 1). A piece of reflective tape was placed on the golf ball enabling the instant of impact to be ascertained.

Two force plates (Kistler, 9281CA), one under each foot of the golfer and synchronised with Vicon, collected ground reaction force data at 1000 Hz. Two sections of golf mat, each equal in size to the force plates, were securely attached to the surface of the force plates. Before each trial a calibration procedure was carried out whereby a zero level of force was defined with only the golf mat in contact with the force plate.

Golfers wore their own golf shoes and glove and used the same brand golf ball (Titelist, ProV1). The golfers hit from the golf mat into a net positioned approximately four metres away; a vertical line was placed on the net to provide 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 parallel to the target line but directed away from the target, the Y-axis directed anteriorly and the Z-axis directed vertically upwards. A launch monitor (TrackMan, ISG Company, Denmark) gathered measures of performance. The launch monitor was positioned three metres in the direction of the GCS X-axis away from the ball and was positioned on the target line at the same height as the golf mat. A reflective dot was placed on the golf ball facing towards the launch monitor in accordance with the manufacturer's instructions.

After each golfer had performed their own warm up, golfers were instructed to address the ball in their normal stance position and to hit a full shot as accurately as possible (i.e. towards the target) with their driver. The golfer then performed 10 shots with their driver, with a one minute rest between shots. Following each shot, the golfer gave a subjective rating of shot quality on a 10-point scale (1–10) where the highest rating was considered representative of their best shot.

Data analysis

Five trials per golfer were analysed based on the quality of the data and high subjective ratings of shot quality. Marker positions were labelled using Vicon Nexus and further processing, including model building, were performed using Visual3D (C-motion Inc, USA). The golfer model comprised 16 segments (head, 2× upper arm, 2× lower arm, 2× hands, 2× thigh, 2× shank and 2× feet, trunk, pelvis and golf club). Whole body COG, was the estimated weighted sum of individual segments in accordance with Dempster's regression equations and the Hanavan model of the human body (Hanavan, 1964; Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2014). Whole body COG was projected onto the laboratory floor global horizontal plane. The golf club was included in the COG determination, as had been done in previous studies of cricket batsmen (Taliep, Galal, & Vaughan, 2007). For modelling purposes, golf club head weight was approximated at 0.20 kg and the shaft (including grip) as 0.15 kg which are within ranges stated for average club head and shaft weights in previous studies (Betzler, 2010; Harper, Roberts, & Jones, 2005). The COG locations of the club head and shaft were estimated as mid-way between the club head heel and toe markers and mid-way between grip and hosel markers, respectively.

Force plate co-ordinate systems were transformed into the laboratory GCS and a global COP was computed from combining both force plates (Exell, Gittoes, Irwin, & Kerwin, 2012). The COP and COG were defined along the X-axis (ML) and Y-axis (AP) of the GCS. In the ML direction, COP_{ML} and COG_{ML} were defined as a percentage of the distance between the X-coordinates of the mid-point of the front (0%) and back (100%) foot at set-up. In the AP direction, COP_{AP} and COG_{AP} were defined as a percentage distance between the Y-coordinates of the furthest back heel (0%) and furthest forward toe (100%) markers of the front and back foot at set-up. Each swing was temporally aligned between take-away (TA) to top of the backswing (TB), TB to impact (IMP) and IMP to mid-follow through (MidFT) using a piecewise linear length normalisation procedure (Helwig, Hong, Hsaio-Wecksler, & Polk, 2011) to 501 normalised time points. The phases of the golf swing were defined using the following threshold functions in Visual3D: TA when the X-component of velocity of the clubhead heel marker (i.e. horizontal velocity in the GCS X-axis direction) first exceeded 0.2 ms^{-1}; TB when the X-component of velocity of the clubhead heel marker changed from negative to positive; IMP as the time point immediately preceding the frame where ball positional data changed; MidFT when the club shaft (defined as a vector between a marker on the grip and hosel) was parallel to the GCS X-axis. Between TA and TB there were 410 normalised time points, TB and IMP there were 70 time normalised time points, and IMP and MidFT there were 21 normalised time points.

Statistical analysis

In this study, it was of interest to determine the extent of inter-golfer variation in COP and COG time-series data in ML and AP directions throughout the swing. As such, for each golfer, an $n \times p$ data matrix was formed where n was the number of trials (n = 5) and p each normalised time point throughout the swing (p = 501). This was done for each variable (COP_{ML}, COG_{ML}, COP_{AP} and COG_{AP}).

Matrices for each golfer were then vertically concatenated to form a single 110 × 501 data matrix representing all the golfers' data for a given variable. This matrix was used as input to the PCA MATLAB function (MATLAB, The Mathworks, Natick, MA). A maximum number of 109 PCs were computed; however only PCs which cumulatively explained at least 90% of the variance were retained for further analysis (Deluzio & Astephen, 2007; Lynn et al., 2012).

Principle component analysis (PCA) generates a series of principal components (PC1, PC2, and PC3…), each explaining a percentage of the variation in the original data. Each PC is defined by a loading factor, a series of positive or negative values which indicate the magnitude and direction of variation in movement patterns relative to the mean data curve at every time increment. A loading factor therefore contains the same number of data points as the original data and the larger the loading factor the greater the variability in the data. A loading factor close to zero contributes little to the PC and indicates that there was little difference in the movement patterns at that stage in the swing. PCA also computes a score for each data set, in this case for each trial by every golfer, for each PC. A large positive (+ve) or negative (–ve) PC score indicates a golfer whose data curve for that trial is further away from the mean curve in the portions of the swing that have higher loading factors. The sign of the PC score, in tandem with the sign of the loading factor, dictates the direction of change from the mean curve.

Qualitative biomechanical interpretation of PCs was achieved by examining the loading factors for each PC and observing the mean data curves of COP and COG with plus and minus one standard deviation of PC scores multiplied by the loading factor for each PC (Figures 1–3).

Pearson's correlation was performed to examine the relationship between COP and COG PC scores in ML and AP directions with significance set at $P < .05$. The strength of the correlation coefficients (r) were categorised as follows: weak (less than 0.4), moderate (0.41 to 0.7) and strong (0.71 to 1) (Dancey & Reidy, 2011).

A stepwise mixed-effects linear regression model (backward elimination) with individual golfer as a random effect was fitted to clubhead velocity (dependent variable) and standardised PC scores (explanatory variables) to predict whether any of the PCs could explain variation in clubhead velocity.

Results

COP and COG movement patterns

A greater number of PCs were required to explain 90% of the variance in COP parameters (4–5 PCs) compared to COG (2 PCs) parameters (Table I). The biomechanical interpretation of PCs largely related to an offset (i.e. magnitude), timing, rate of change and range in a given parameter (Table I).

Mean curves with plus or minus one standard deviation of the PC score multiplied by the loading factor helped interpret the movement patterns of golfers with either positive or negative PC scores for a specific PC (Robertson et al., 2014) (Figures 1 and 2). The mean curves are colour coded according to the loading factors for that PC. The description of golfers with +ve or –ve PC scores are provided in Table I and also graphically shown in Figures 1 and 2.

Relationship between COP and COG principal Components

The only two strong correlations were between COG_{ML} and COP_{ML} PC1 scores (i = 0.92, $P < .05$) and COP_{AP} and COG_{AP} PC1 scores (r = 0.81, $P < .05$) (Figure 3(a) and 3(b)). For brevity only the relationship between COG_{ML} and COP_{ML} will be presented and is explored in greater detail in Figure 3(c)–3(f). Golfer 7 and Golfer 8 were chosen to explore the relationship between COG_{ML} and COP_{ML} PC1 scores as they had opposing scores (Figure 3(a)). Golfer 7 had low negative COG_{ML} and COP_{ML} PC1 scores. The PC score relationship for this golfer showed that in the backswing, there was greater movement of COG_{ML} to the back foot coupled with a greater range in COP_{ML} to the back foot whereby COP_{ML} moved beyond the COG_{ML} position. At IMP, COG_{ML} was closer to mid- stance (~50%) and was coupled with a reversal of COP_{ML} from front foot to back foot during the downswing (Figure 3(c) and 3(e)). Golfer 8 had high positive COG_{ML} and COP_{ML} PC1 scores. This relationship showed that less movement of the COG_{ML} towards the back foot was coupled with less movement of the COP_{ML} onto the back foot and COP_{ML} moved beyond COG_{ML}. During the downswing, the COG_{ML} continued to move towards the front foot and was coupled with greater movement of the COP_{ML} ahead of COG_{ML} and towards the front foot.

Relationship between COP, COG principal components and clubhead velocity

The overall mean clubhead velocity across all golfers, measured by TrackMan, was 45.46 ± 2.54 ms^{-1}. From the regression analysis of the predictor PCs, three were significant and predicted 74% of the variance in clubhead velocity (adjusted r^2 = 0.742, $P < .001$). The most important predictor of clubhead velocity was COP_{ML} PC3 (β = 0.449, s_{x-} = 0.186, $P < .05$) and would give the greatest increase (relative to standard deviation) in clubhead velocity. Golfers whose COP was closer to their back foot in the mid-backswing would have higher clubhead velocities. The second most important predictor was COG_{ML} PC2 (β = −0.399, s_{x-} = 0.201, $P < .05$); however this would decrease clubhead velocity. Hence, golfers with early COG movement towards the front foot before TB would have lower clubhead velocity. Lastly, COP_{ML} PC2 (β = 0.323, s_{x-} = 0.156, $P < .05$) would increase clubhead velocity (relative to standard deviation). Hence, golfers with early movement of COP to front foot in back- swing would have higher clubhead velocity. Neither the PC scores in AP direction nor the PC1 scores in the ML direction appeared to be significant predictors of clubhead velocity.

Discussion

The purpose of this study was to identify and compare golfers' COP and COG movement patterns throughout the golf swing in ML and AP directions using PCA and examine the relationship with measures of performance.

Movement patterns represented by positive and negative COP_{ML} PC1 scores resembled the front foot and reverse foot styles, respectively, reported by Ball and Best (2007a, 2007b). This result confirms the identification of two extremes of ML COP movement, for a group of similar ability golfers (Figure 3).

Golfers, however, featured on a continuum between these two extremes as can be seen by the spread in PC1 scores on the scatterplot in Figure 3(a) and cannot be categorised clearly into either of these extreme styles. The timing and rate of change in COP_{ML} (PC2 and PC3) in the backswing and down- swing were also key features of COP_{ML} (Table I). Previous studies have found significant correlations between clubhead velocity and the velocity of COP_{ML} at discrete stages in the early downswing or late backswing (Ball & Best, 2012). The benefits of the PCA approach used in this study are that PCs capture these key features (variances) wherever they occur during the swing. These can subsequently be used to investigate relationships with performance measures (such as in clubhead velocity presented herein) or with other kinematic/kinetic variables.

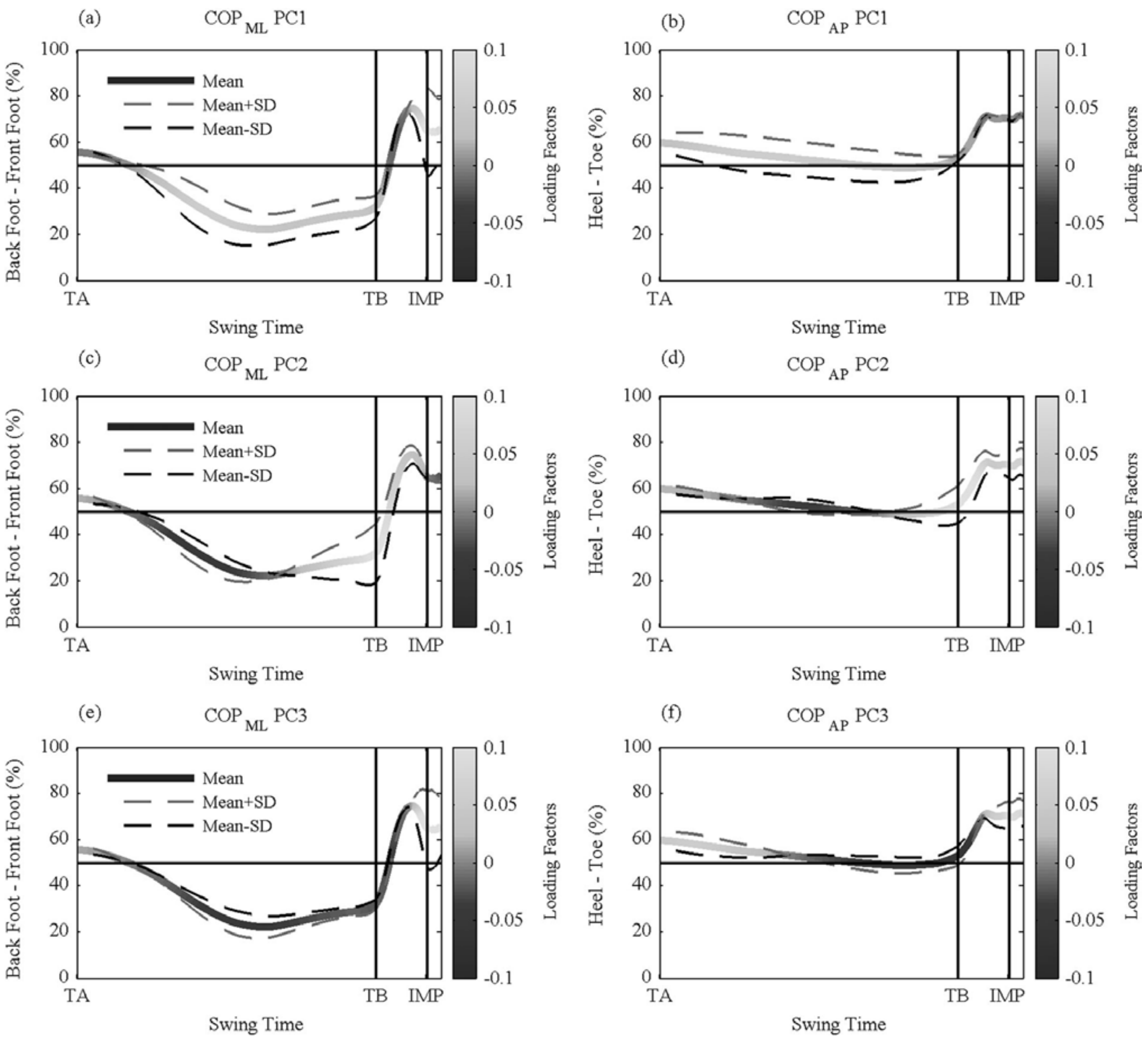

Figure 1. Mean curve (colour graded by PC loading factor) ± one SD of PC scores multiplied by loading factors for COPML and COPAP (a and b), PC1 (c and d), PC2 and (e and f) PC3, respectively. Golfers with PC scores of mean + one SD followed dashed grey line and those with PC scores of mean – one SD followed the dashed black line.

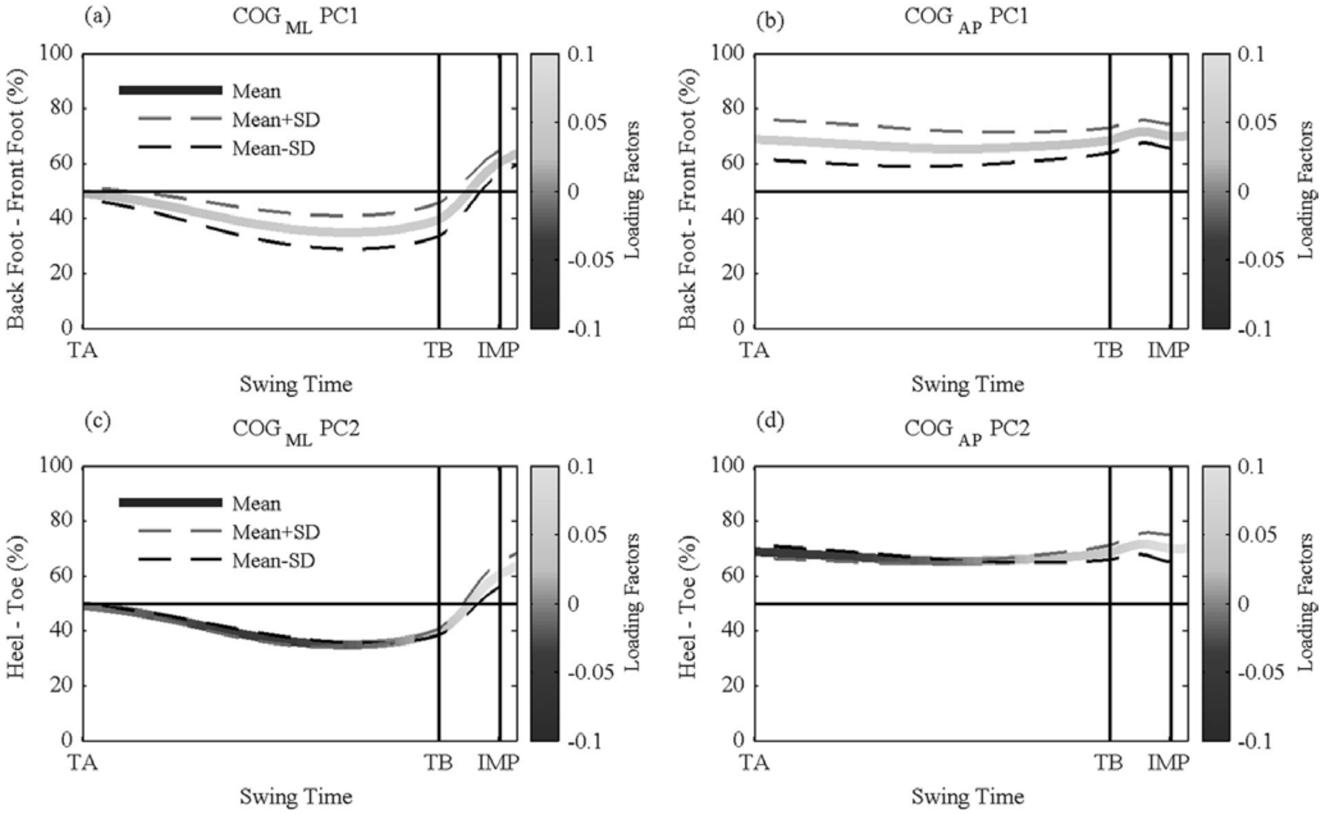

Figure 2. Mean curve (colour graded by PC loading factor) ± one SD of PC scores multiplied by loading factors for COG_{ML} and COG_{AP} (a and b) PC1 and (c and d) PC2, respectively. Golfers with PC scores of mean + one SD followed dashed grey line and those with PC scores of mean – one SD followed the dashed black line.

Eighty-four per cent of variance was explained by COG_{ML} PC1 and described the position of COG throughout the swing. The ML COG pattern captured by PC1 is similar to the pattern described by Burden et al. (1998) and the distinguishing difference between high- and low-handicap golfers captured using the methods of Choi et al. (2016). Examining the strong linear relationship (r = 0.92) between COP and COG_{ML} PC1 scores in this study can help to understand this movement pattern further (Figure 3(a)). At TA, COG_{ML} is evenly positioned between front and back foot before moving towards the back foot and as such COP moves beyond the COG position (i.e. closer to the back foot). During the downswing, the COP begins to move ahead of the COG towards the front foot and the extreme styles see golfers either align COP and COG at impact (–ve PC1 scores) or COP stays ahead of the COG and both are closer to the front foot (+ve PC1 scores) at IMP. Welch, Banks, Cook, and Draovitch (1995) reported the interaction of ML COP and COG in baseball hitters as a measure of dynamic balance. Baseball hitters who aligned COP and COG evenly between the feet near impact emphasised rotational body movements, whereas hitters with COG and COP towards the front foot emphasised more linear body movement. The rotational movements and alignment of COP and COG were deemed to increase the force couple applied to the pelvis and facilitate pelvis rotational acceleration whereas linear movement meant force was only applied through the front foot when striking the baseball (Welch et al., 1995). Given the outcome of a baseball swing is also to strike the ball as far as possible it is interesting to note the similarities between the results of this study and those of Welch et al. (1995). Therefore, it would also be of interest to compare a golfer's body rotation variables to their COP and COG.

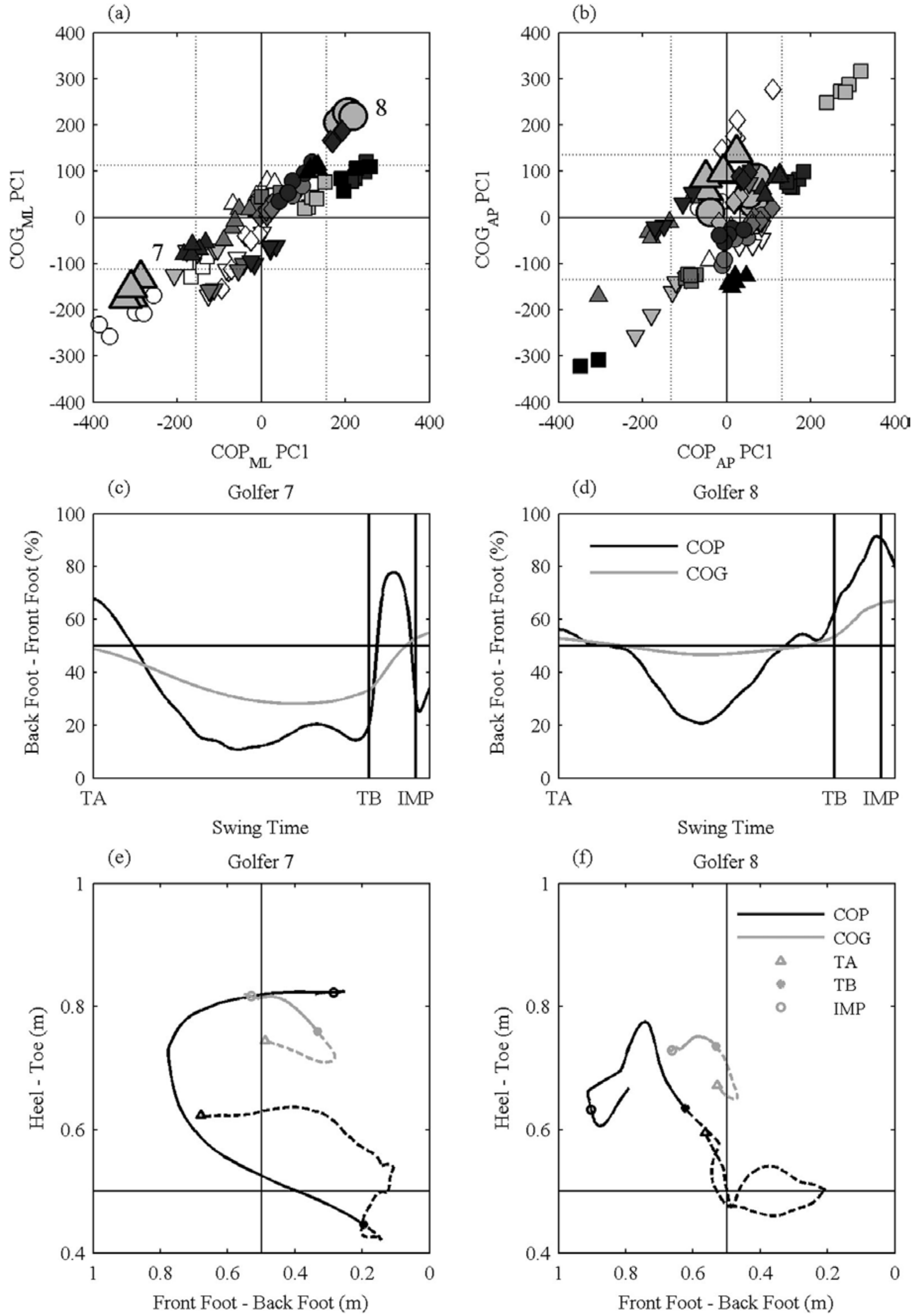

Figure 3. Scatterplot of PC1 scores for (a) COG_{ML} and COP_{ML} and (b) COP_{AP} and COG_{AP}. Dashed lines represent one SD of the PC scores (c) COP and COG overall movement traces for Golfer 7 and (d) Golfer 8, (e) Golfer 7 ML COP and COG trajectories and (f) Golfer 8 ML COP and COG trajectories.

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Table I. Percentage variance explained (%), general biomechanical interpretation of COP and COG principal components (PCs) and positive and negative PC scores in medial-lateral (ML) and anterior-posterior (AP) directions throughout the swing. TB = top of the backswing, IMP = impact, TA = takeaway.

Parameter	PC	%	Biomechanical Interpretation	Positive PC Score	Negative PC Score
COP_{ML}	1	37.8	Position TA to TB and rate of change and direction TB to IMP	Less movement to back foot between TA to TB. Closer to front foot at IMP	More movement to back foot TA to TB. Movement to front foot near TB, rapid movement to mid stance before IMP
	2	22.5	Timing and position from TA to TB and rate of change TB to IMP	Early movement to back foot TA to mid-backswing, movement towards front foot mid-backswing to mid-downswing	Late movement to back foot and rapid movement towards front foot near TB
	3	18.0	Position mid-backswing and rate of change and direction from mid-downswing to IMP	Position closer to back foot mid-backswing. Rapid movement to front foot TB to IMP	Position closer to front foot at mid-backswing, movement to front foot near TB before movement to mid stance before IMP
	4	6.8	Range of COP in backswing and rate of COP to front foot before TB	Greater movement towards back foot mid-way between TA to TB early movement to front before TB	Less movement towards back foot mid-way between TA to TB late movement to front before TB
	5	5.6	Rate of COP to front foot before TB and through IMP	-	-
COP_{AP}	1	46.1	Position between TA to TB and timing before TB	Position towards heels between TA to TB. Late movement towards toes	Position towards toes TA to TB. Early movement to toes before TB
	2	18.0	Timing and rate of change towards toes before TB to IMP	Early and gradual movement towards toes before TB and closer to toes at IMP	Late and rapid movement towards toes near TB and closer to heels at IMP
	3	14.8	Timing and rate of change towards heels from TA to TB and position at IMP	Greater movement from toes to heels in backswing and closer to toes at IMP	Stable position until near TB and less shift towards toes at IMP
	4	11.4	Position in backswing and rate of change towards toes before IMP	-	-
COG_{ML}	1	83.8	Position throughout swing	Less movement towards back foot in backswing and closer to front foot at IMP	More movement towards back foot in backswing and closer to mid-stance at IMP
	2	10.4	Timing towards front foot before TB and position between TB to IMP	Early movement to front foot before TB and closer to front foot at IMP	Late movement to front foot after TB and closer to mid foot at IMP
COG_{AP}	1	83.5	Position throughout swing	Nearer toes. In downswing, shifted slightly towards heels before movement to toes	Further towards heels. In downswing, shifted slightly towards heels before movement to toes
	2	12.1	Timing of movement between TA and TB and position between TB - IMP	COG_{AP} positioned towards toes mid-backswing and near toes between TB and IMP	COG_{AP} positioned towards heels mid-backswing and closer to mid foot between TB and IMP

Golfers typically positioned COP_{AP} closer to the toes at TA (~60%) before a slight shift to the heels in the backswing, moving towards the toes in the downswing and remaining relatively stable through IMP (Figure 1(b)). The movement pattern varied in magnitude in the backswing (PC1), timing of COP_{AP} movement before TB (PC2) and range of COP_{AP} movement in the late backswing to early downswing (PC3). Lynn et al. (2012) reported similar timings of peak vertical and peak posterior force in early downswing differentiated high- and low-skilled golfers and was thought to help create a force couple to facilitate body rotation. Whilst the measures used in this study are not directly comparable to Lynn et al.'s (2012) study, there is evidence to support that the timing of AP COP (PC2 scores) can also distinguish between golfers of similar ability and hence may be used to identify strengths or weaknesses in golfers movement patterns. In the downswing, there was a small shift in COG_{AP} movement which varied in magnitude (PC1 and PC2) (Figure 2(b) and 2(d)). This COG movement may indicate a golfer's ability to react to the high forces of the club (radial and centripetal) before impact (Hellström, 2009) and PC scores could identify golfers who can reasonably do this. The relationship between AP COP and COG PC1 (r = 0.81) scores shows that the small shift in COG_{AP} during the downswing (Figure 2(b)) coincides with a relatively stable period in COP_{AP} (Figure 1(b)). This relationship may further suggest that at this swing instance, the greatest requirement is to resist the large club forces rather than generate forces to create body rotation.

From regression analysis, 74% of clubhead velocity was explained by three PCs. The range in COP_{ML} in the backswing and rate of change in COP_{ML} in the downswing (PC3) were the greatest predictors of clubhead velocity. Ball and Best (2012) found that a larger mediolateral COP velocity at early downswing was an important predictor of clubhead velocity for some golfers. The results of this study would support the coaching notion that increasing the rate of COP_{ML} towards the front foot during early downswing could increase clubhead velocity (Jenkins, 2008). A more positive COP_{ML} PC2 score (i.e. early movement of COP to front foot in backswing) was positively related to clubhead velocity. This finding is similar to Lynn et al.'s (2012) PCA results where they observed early unloading of vertical force under the back foot in the backswing of highly skilled golfers. The authors concluded that early movement of vertical force onto the front foot was more effective in allowing the sequence of body rotations. Conversely, early COG movement towards the front foot (+ve COG_{ML} PC2) was found to decrease clubhead velocity. This finding could relate to Lynn et al.'s (2012) study that found the timing and direction of ground reaction forces was a key feature of highly skilled golfers. Force couples that encourage too early lateral movement of COG could hinder generation of clubhead velocity. Whilst there is a strong relationship between COP and COG PC1 scores neither were significant predictors of clubhead velocity. Interestingly Golfer 7 and Golfer 8, with opposing PC1 scores, had similar average clubhead velocity (49.6 ± 0.5 ms^{-1} and 48.4 ± 0.6 ms^{-1}, respectively) and were both approximately 3 ms^{-1} quicker than the overall average across all golfers. Similarly, AP PCs were also not related to clubhead velocity. As coaches also stated that dynamic balance could affect accuracy (Smith et al., 2015), future studies should investigate the relationship between COP and COG PCs and other measures of performance related to shot accuracy.

In conclusion, this study used PCA and showed the greatest variation in COP movement patterns in ML and AP directions was related to magnitude, timing and rate of change throughout the golf swing. The golfers' COG movement patterns were relatively similar in shape and typically differed in magnitude or timing of movement. The relationship between COP_{ML} and COG_{ML} PC1 scores identified different extremes of COP and COG movement in golfers and could be an indication of how golfers achieve dynamic balance either with more lateral or rotational movement. Golfers displaying early movement of ML COP to the front foot in the backswing (PC2) or greater range and rate of movement to the front foot in the downswing (PC3) were more likely to have higher clubhead velocity. Golfers that moved their COG towards the front foot earlier in the backswing, however, were more likely to have lower clubhead velocity. Future studies using PCA should investigate the relationships between these PCs, golfer kinematic variables and other measures of performance.

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Appendix 1

Table AI. Golfer marker set including marker names, definitions and anatomical placements.

Marker	Definition	Anatomical placement
RFHD	Right front head	Right temple
LFHD	Left front head	Left temple
RBHD	Right back head	Right back of head
LBHD	Left back head	Left back of head
RAC	Right acromion	Bony prominence of right shoulder
LAC	Left acromion	Bony prominence of left shoulder
CLAV	Clavicle	Top of the breast bone
STRN	Sternum	Base of breast bone
C7	7th cervical vertebrae	Prominent vertebrae at base of neck
T2	2nd thoracic vertebrae	Two vertebrae below C7
T8	8th thoracic vertebrae	Two vertebrae above T10
T10	10th thoracic vertebrae	Centre of mid-back
L4	4th lumbar vertebrae	One vertebrae above L5
L5	5th lumbar vertebrae	Last vertebrae above sacrum
LSHO	Left shoulder	Lateral side of left shoulder at shoulder joint centre level
RSHO	Right shoulder	Lateral side of right shoulder at shoulder joint centre level
RBAK	Right back	Right back over right scapula
LUP1	Left upper arm 1	Posterior side of left upper arm
LUP2	Left upper arm 2	Lateral side of left upper arm above epicondyle
RUP1	Right upper arm 1	Posterior side of right upper arm
RUP2	Right upper arm 2	Lateral side of right upper arm above epicondyle
LLELB	Left lateral elbow	Left lateral elbow epicondyle
LMELB	Left medial elbow	Left medial elbow epicondyle
RLELB	Right lateral elbow	Right lateral elbow epicondyle
RMELB	Right medial elbow	Right medial elbow epicondyle
LFA	Left forearm	Posterior side of left forearm

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RFA	Right forearm	Posterior side of right forearm
LRAD	Left radius	Left radial epicondyle
RRAD	Right radius	Right radial epicondyle
LULN	Left ulna	Left ulna epicondyle
RULN	Right ulna	Right ulna epicondyle
LHA	Left hand	Dorsum of left hand below head of 2nd metacarpal
RHA	Right hand	Dorsum of right hand below head of 2nd metacarpal
LASIS	Left anterior superior illiac spine	Bony prominence of the left anterior superior iliac
RASIS	Right anterior superior illiac spine	Bony prominence of the right anterior superior iliac
LPSIS	Left posterior superior iliac spine	Bony prominence of the left posterior superior iliac
RPSIS	Right posterior superior iliac spine	Bony prominence of the right posterior iliac
LTH1	Left thigh 1	Lateral side of left thigh ≈0.1m under greater trochanter
LTH2	Left thigh 2	Medial side of left thigh between vastus medialis and rectus femoris
LTH3	Left thigh 3	Left vastus lateralis tendon
RTH1	Right thigh 1	Lateral side of right thigh ≈0.1m under greater trochanter
RTH2	Right thigh 2	Medial side of right thigh between vastus medialis and rectus femoris
RTH3	Right thigh 3	Right vastus lateralis tendon
LLK	Left lateral knee	Left lateral knee epicondyle
RLK	Right lateral knee	Right lateral knee epicondyle
LMK	Left medial knee	Left medial knee epicondyle
RMK	Right medial knee	Right medial knee epicondyle
LSK1	Left shank 1	Lateral side of left shank
LSK2	Left shank 2	Lateral side of left shank
LSK3	Left shank 3	Lateral side of left shank
LSK4	Left shank 4	Lateral side of left shank
RSK1	Right shank 1	Lateral side of right shank
RSK2	Right shank 2	Anterior side of right shank
RSK3	Right shank 1	Lateral side of right shank
RSK4	Right shank 1	Lateral side of right shank
LLA	Left lateral ankle	Left lateral malleolus
LMA	Left medial ankle	Left medial malleolus
RLA	Right lateral ankle	Right lateral malleolus
RMA	Right medial ankle	Right medial malleolus
LTOE	Left toe	Dorsum of left foot below 2nd metatarsal
RTOE	Right toe	Dorsum of right foot below 2nd metatarsal
RHEEL	Right heel	Posterior side of right heel
LHEEL	Left heel	Posterior side of left heel