

ARTICLE POSTPRINT

## The role of pelvis-thorax coupling in controlling within-golf club swing speed

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### ABSTRACT

Pelvis-thorax coordination has been recognised to be associated with swing speed. Increasing angular separation between the pelvis and thorax has been thought to initiate the stretch shortening cycle and lead to a more forceful downswing. The purpose of this study was to determine whether pelvis-thorax coupling played a significant role in scaling single-club swing speed in a group of low-handicap golfers (mean handicap = 4.1). Sixteen participants played shots to target distances determined based on their typical 5- and 6-iron shot distances. Half the inter-club distance was used to create three swing effort conditions: ‘minus’, ‘norm’, and ‘plus’. Ten shots were played under each swing effort condition using both the 5-iron and 6-iron, resulting in six shot categories and 60 shots per participant. No significant differences were found for X-factor for either club or swing effort. X-factor stretch showed significant differences for both club and swing effort. Continuous relative phase (CRP) results mainly showed evidence of the stretch shortening cycle in the downswing and that it was more pronounced late in the downswing as swing effort increased. Inter-individual variability in CRP curves was substantial, demonstrating the need for individual analyses when investigating complex coordination patterns such as the golf swing.

### KEYWORDS

X-factor; coordination; sports biomechanics; continuous relative phase; statistical parametric mapping

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## 1. Introduction

X-factor was a term introduced in the early 1990s by golf coach Jim McLean, which refers to the relative angular displacement between the pelvis and thorax about an axis

assumed to run approximately through the spine. McLean noted that golfers on the PGA TOUR who demonstrated a large difference between pelvis and thorax position at the transition from the backswing to the downswing seemed to be golfers known for their driving distance (McLean, 1992). Since the term was coined, much research has focused on the relationship between pelvis-thorax kinematics and clubhead speed.

Several studies have shown X-factor to have a strong relationship with clubhead or ball speed (Brown et al., 2011; Chu, Sell, & Lephart, 2010; Myers et al., 2008), although some have reported conflicting results (Kwon, Han, Como, Lee, & Singhal, 2013). Ironically, X-factor studies have largely not been able to distinguish between skill levels (Cheetham, Martin, Mottram, & St. Laurent, 2001; Cole & Grimshaw, 2009; Egret, Weber, Dujardin, & Chollet, 2004; McTeigue, Lamb, Mottram, & Pirozzolo, 1994), despite the well-established strong correlation between clubhead speed and handicap (Brown et al., 2011; Fradkin, Sherman, & Finch, 2004), with the exception of Zheng, Barrentine, Fleisig, and Andrews (2008) who found a significant difference only in the two extreme skill groups (professional vs. high-handicap). Additionally, X-factor has not distinguished between males and females (Egret, Nicolle, Dujardin, Weber, & Chollet, 2006; Horan, Evans, Morris, & Kavanagh, 2010).

Although Cheetham et al. (2001), who compared two small groups of highly skilled and less skilled golfers, did not find a statistically significant difference in X-factor between the groups, the amount pelvis-thorax angular separation increased during the downswing did distinguish between the groups. The authors called the increase between these segments the *X-factor stretch* – during the early downswing the angular separation was stretched as the more proximal pelvis segment began rotating toward the target slightly before the thorax. The increase in separation between the pelvis and thorax is thought to initiate the stretch-shortening cycle in the downswing, which increases the range of motion of the thorax relative to the pelvis, thereby increasing work done, kinetic energy and axial speed during the downswing. Pre-stretching the muscles involved also enables the concentric contraction phase to begin with a higher active state and force value (van Ingen Schenau, Bobbert, & de Haan, 1997).

Currently, the literature seems to suggest that one does not have to be an elite level golfer to achieve X-factor values (at the top of the backswing) similar to those of many professional and elite-level amateur golfers. However, to initiate the stretch-shortening cycle, the golfer must have the desired relative pelvis-thorax position (X-factor) as well as a sufficient absolute position of each segment so that the proximal to distal sequence during the downswing can occur (see Brown et al., 2011, for a discussion of the stretch shortening cycle in female golfers).

As is common in biomechanics research, the emphasis on X-factor studies has been on maximising performance – in particular, clubhead speed at impact (e.g. Meister et al., 2011; Sprigings & Mackenzie, 2002). However, in golf a skill that is arguably more important than maximum distance is distance control. In a typical round of golf, golfers will often find themselves with target distances that do not match the preferred distance of any of their clubs and must, therefore, modify their swing. If a golfer encounters a distance exactly between the preferred distance of two clubs he or she is faced with either hitting the shorter club harder or the longer club easier (assuming enough skill on the part of the golfer to be sensitive to half-club distance increments). Therefore, one focus of this study was how the pelvis-thorax coupling changes with forced changes in swing effort – similar to what would be found in real playing conditions.

Recently, angle-angle diagrams (Horan, Evans, & Kavanagh, 2011), phase portraits (Horan et al., 2010) and continuous relative phase (CRP)(Choi, Lee, Choi, & Mun,

2016) have been used to investigate motor control underlying the pelvis-thorax coupling. This study looks at whether a higher-order coupling between pelvis and thorax, as represented by CRP, is involved or whether the range of motion is simply parameterised to adjust swing speed by individual low-handicap golfers.

## 2. Methods

### 2.1. *Participants*

Sixteen male right-handed golfers (age =  $28 \pm 7.0$  years, handicap =  $4.1 \pm 4.0$ , range +2.5–10.0) took part in the study. The sample size was chosen based on the  $4^\circ (\pm 4^\circ)$  difference in X-factor between ‘easy’ and ‘hard’ swings found by Meister et al. (2011). All golfers were healthy and free of any injuries. Each gave informed written consent before participating and the Faculty of Medicine’s Ethical Commission at the Technische Universität München (Munich, Germany) approved all procedures of the study.

### 2.2. *Task*

Each golfer played preliminary shots with a 5- and 6-iron to establish typical distances with each club. Median values were used as typical distances for each club ( $d_5$  and  $d_6$ , respectively in Table 1). Based on these distances, the participants were required to perform shots with a 5- and 6-iron to their typical distances as well as to distances adjusted by half the distance interval between the clubs, which was, on average, 5.9 m (Table 1). Each golfer played ten shots to each of the shot categories in a randomised order from a golf hitting mat to an indoor net. A FlightScope Prime launch monitor (EDH Ltd., Stellenbosch, South Africa) was used to estimate the shot distances. Participants were provided with the estimated distances after each shot. The volume ( $6 \text{ m} \times 4 \text{ m} \times 4 \text{ m}$ ) of the net allowed at least 6 m of ball flight to be seen by the golfer and tracked by the launch monitor. New Bridgestone B330 golf balls were used for each testing session. Metallic stickers were placed on each ball in accordance with manufacturer recommendations.

### 2.3. *Data collection and processing*

An eight-channel Polhemus Liberty electromagnetic motion tracking system (Polhemus, Colchester, USA) was used to collect kinematic data at 240 Hz. Five sensors were placed on the following landmarks: posterior aspect of the lead hand, lateral aspect of the lead upper arm, T3, L4 and centre of the forehead. The thorax and pelvis sensors were housed in a non-stretching, fabric belt, which ensured the sensors represented pelvis and thorax motion, respectively. The source transmitter was placed approximately 0.3 m behind the golfer. The anatomical landmark digitisation protocol was consistent with Evans, Horan, Neal, Barrett, and Mills (2012). The belt mounted sensor on the pelvis has been shown to be valid and reliable for measuring pelvis motion (Sprigle, Wootten, Bressler, & Flinn, 2002); this general landmark digitisation technique has also been shown to be both valid and reliable for defining anatomical axes (Adhia, Bussey, Ribeiro, Tumilty, & Milosavljevic, 2013). Also note that the sensors track the landmark positions, which are used to define the respective

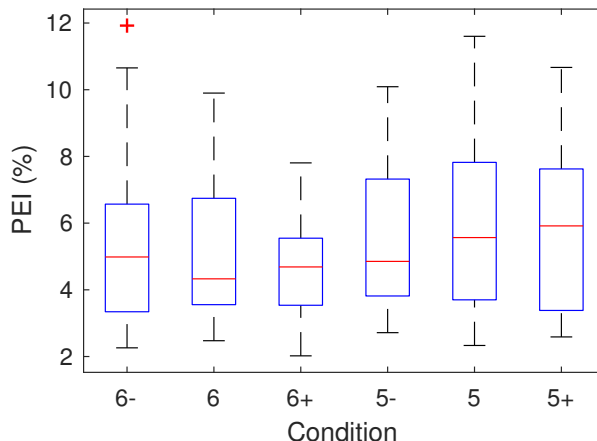
segment (e.g. pelvis) coordinate systems, so the position of the sensor relative to the landmarks is unimportant.

The lab coordinate system was defined with  $+X$  directed away from the target and parallel with the target axis,  $+Y$  directed anteriorly and perpendicular to  $X$  and  $+Z$  vertically upward. The thorax coordinate system was defined as follows: the  $x$ -axis was directed through the left and right humeral heads with the origin midway between them. The  $y$ -axis was the cross product of  $x$  and a vector directed superiorly and parallel with the midline. The  $z$ -axis was the cross product of  $x$  and  $y$ . The  $x$ -axis of the pelvis segment ran through the left and right greater trochanters with the origin midway between them. The  $y$ -axis of the pelvis was the cross product of  $x$  and a vector directed superiorly through the left greater trochanter and the lateral aspect of the left iliac crest. The  $z$ -axis of the pelvis was the cross product of  $x$  and  $y$  (as described in Evans et al., 2012).

Rotations about the pelvis and thorax  $z$ -axes were subsequently used for calculating their angular separation (X-factor) and CRP. The start of the swing was defined as the first frame in which the velocity vector of the pelvis about the  $z$ -axis remained positive until the top of the backswing. We trimmed the last frame at release  $-40$  frames after impact. The centred Hilbert transform method as outlined in Lamb and Stöckl (2014) was used to calculate CRP between the pelvis and thorax to reduce frequency effects from non-circular phase portraits. Kinematic time-series data were aligned at the mean time index of maximum pelvis rotation about the local  $z$ -axis for each participant and time normalised to 201 samples. Kinematic data were calculated using Golf BioDynamics software (Golf BioDynamics Pty Ltd., Brisbane, Australia) running in Windows 7. Further processing and analysis was done in MATLAB (R2016a version 9.0.0, The MathWorks Inc., Natick, MA) on a Mac OS X 10.11.6 operating system.

**Table 1.** Distance calculation for each club and swing effort combination.  $d_5$  and  $d_6$  represent the typical 5- and 6-iron distances for each golfer, respectively.

Club	Swing Effort	Distance	$M \pm SD$ distances (m)
6	minus	$d_6 - \frac{d_5 - d_6}{2}$	$141.1 \pm 7.9$
6	norm	$d_6$	$147.3 \pm 7.8$
6	plus	$d_6 + \frac{d_5 - d_6}{2}$	$153.2 \pm 7.8$
5	minus	$d_5 - \frac{d_5 - d_6}{2}$	$153.2 \pm 7.8$
5	norm	$d_5$	$159.2 \pm 8.2$
5	plus	$d_5 + \frac{d_5 - d_6}{2}$	$165.0 \pm 8.4$



**Figure 1.** Boxplot showing mean percent error index (PEI; see Hellström, 2009) for each condition.

#### 2.4. Statistical analysis

We computed a two-way, repeated measures ANOVA on the maximum absolute values of pelvis and thorax angular displacement to see how range of motion changes with club and swing effort as well as X-factor and X-factor stretch. We chose to use statistical parametric mapping (SPM) (Pataky, 2010) as a time-series statistical analysis method to test the null hypothesis of no effect of club and swing condition. The relationship between pelvis-thorax coupling and club and swing effort across the group was also assessed under a two-way repeated measures ANOVA model. The F statistic was computed at each point in time, forming a single test statistic trajectory ‘ $F(t)$ ’, describing the time-dependent deviations amongst the three effort and two club conditions. The significance of  $F(t)$  was assessed by computing the critical F threshold that smooth Gaussian trajectories would reach in only  $\alpha = 5\%$  of many repeated experiments. If the observed  $F(t)$  exceeded that threshold then the null hypothesis was rejected. Separate two-way ANOVAs for each participant were also conducted to assess intra-individual pelvis-thorax coupling. A Bonferroni correction for multiple comparisons was used to retain a family-wise error of  $\alpha = 0.05$  across the sixteen golfers’ tests.

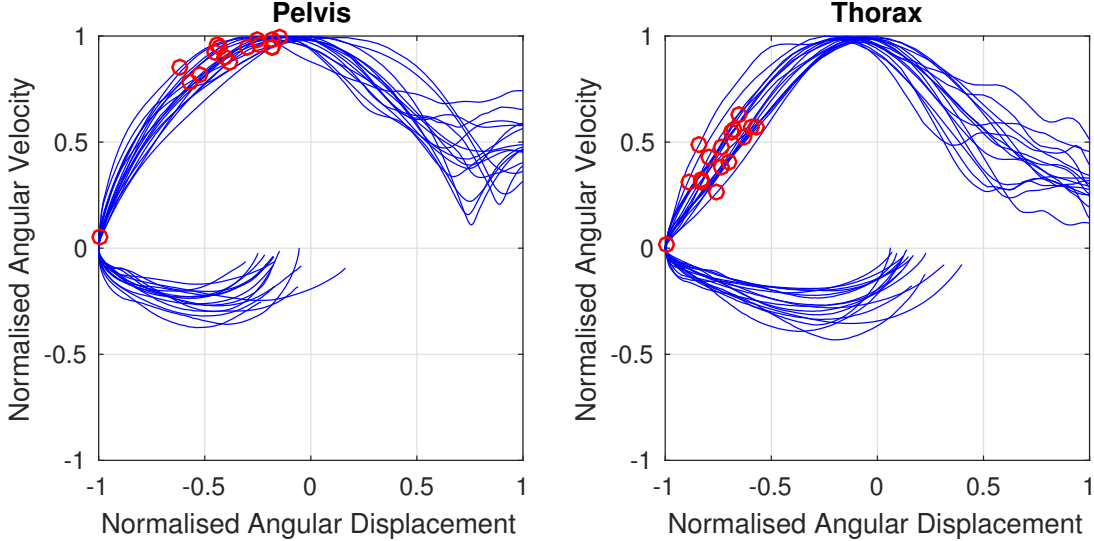
### 3. Results

Percent error index (PEI) allows the errors for different target distances to be compared and was calculated as the resultant position from the respective target distance, divided by the target distance and expressed as a percentage (see Hellström, 2009). PEIs were fairly consistent across club and swing effort conditions (Figure 1), which suggests that the participants were able to adjust their swing according to the task condition, mean PEI = 5.4%, SD = 2.3%. Handicap was correlated with PEI,  $r = .667$ ,  $P < .001$ , 95% CI [.485, .794], indicating lower handicap participants tended to produce lower PEI.

#### 3.1. Range of motion

The two-way repeated measures ANOVA for pelvis range of motion showed significant main effects for swing effort,  $F(2, 30) = 46.4$ ,  $P < .001$ , partial  $\eta^2 = .75$ , and

club,  $F(1, 30) = 13.8, P = .002$ , partial  $\eta^2 = .52$  and a non-significant interaction,  $F(2, 30) = 0.53, P = .594$ , partial  $\eta^2 = .04$ . Similarly, two-way ANOVA for thorax range of motion also showed significant main effects for swing effort,  $F(2, 30) = 20.8, P < .001$ , partial  $\eta^2 = .59$  and club,  $F(1, 30) = 17.3, P < .001$ , partial  $\eta^2 = .62$ ; however, there was a significant interaction,  $F(2, 30) = 5.13, P = .012$ , partial  $\eta^2 = .27$ .



**Figure 2.** Mean phase plane trajectories for each participant: pelvis (left) and thorax (right). Red dots identify the mean time indices at which X-factor stretch occurred for each participant. Normalisation Method A from Lamb and Stöckl (2014) was used for the diagram.

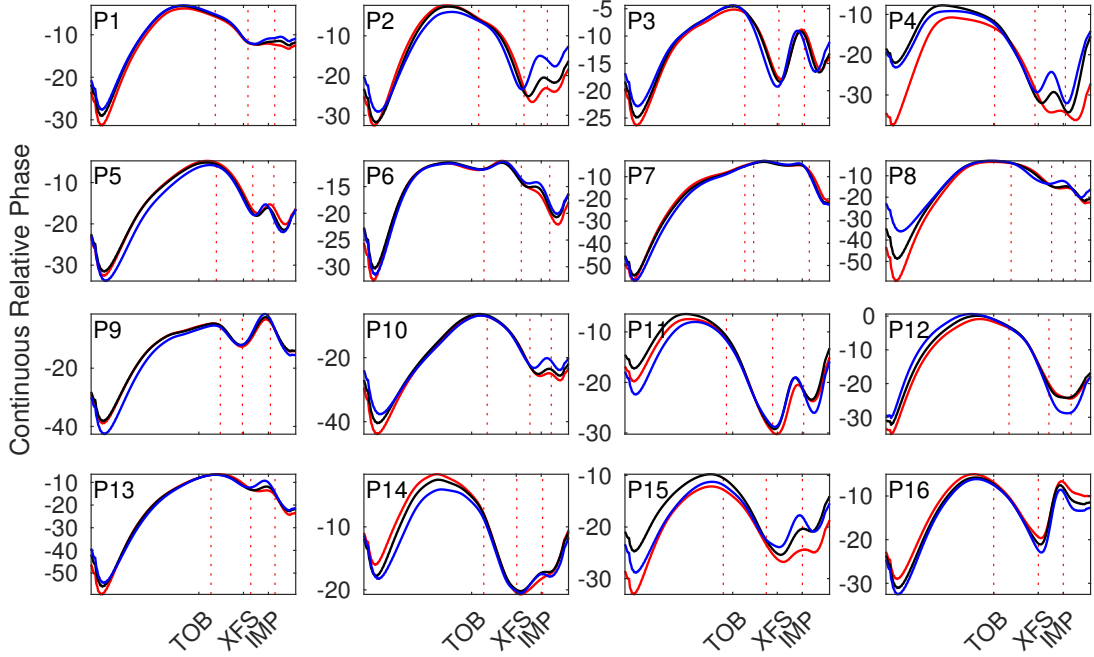
### 3.2. X-factor

There were no significant differences for X-factor between club,  $F(1, 30) = 1.38, P = .267$ , partial  $\eta^2 = .16$  or swing effort conditions,  $F(2, 30) = 0.19, P = .672$ , partial  $\eta^2 = .04$ ; the interaction between club and swing effort was also non-significant,  $F(2, 30) = 0.19, P = .831$ , partial  $\eta^2 = .01$ . For X-factor stretch there were significant differences for both, club,  $F(1, 30) = 6.75, P = .020$ , partial  $\eta^2 = .73$  and swing effort,  $F(2, 30) = 43.4, P < .001$ , partial  $\eta^2 = .27$ ; however, there was a non-significant interaction,  $F(2, 30) = 0.84, P = .440$ , partial  $\eta^2 = .03$ .

### 3.3. Group CRP

The phase plane trajectories were qualitatively similar and non-circular for all participants (Figure 2), which justified using the Hilbert transform method for the phase angle calculation (Lamb & Stöckl, 2014). The trajectories in Figure 2 proceed clockwise and the red dots identify the average time index for X-factor stretch. For all participants, the pelvis led the thorax through phase space. CRP between pelvis and thorax is a higher order measure of their coupling than X-factor and was used to characterise their coordination. Mean CRP curves for all participants are shown in Figure 3; CRP values were negative for all participants indicating the proximal segment (pelvis) led the distal (thorax) through phase space.

The SPM two-way repeated measures ANOVA was conducted across the group using



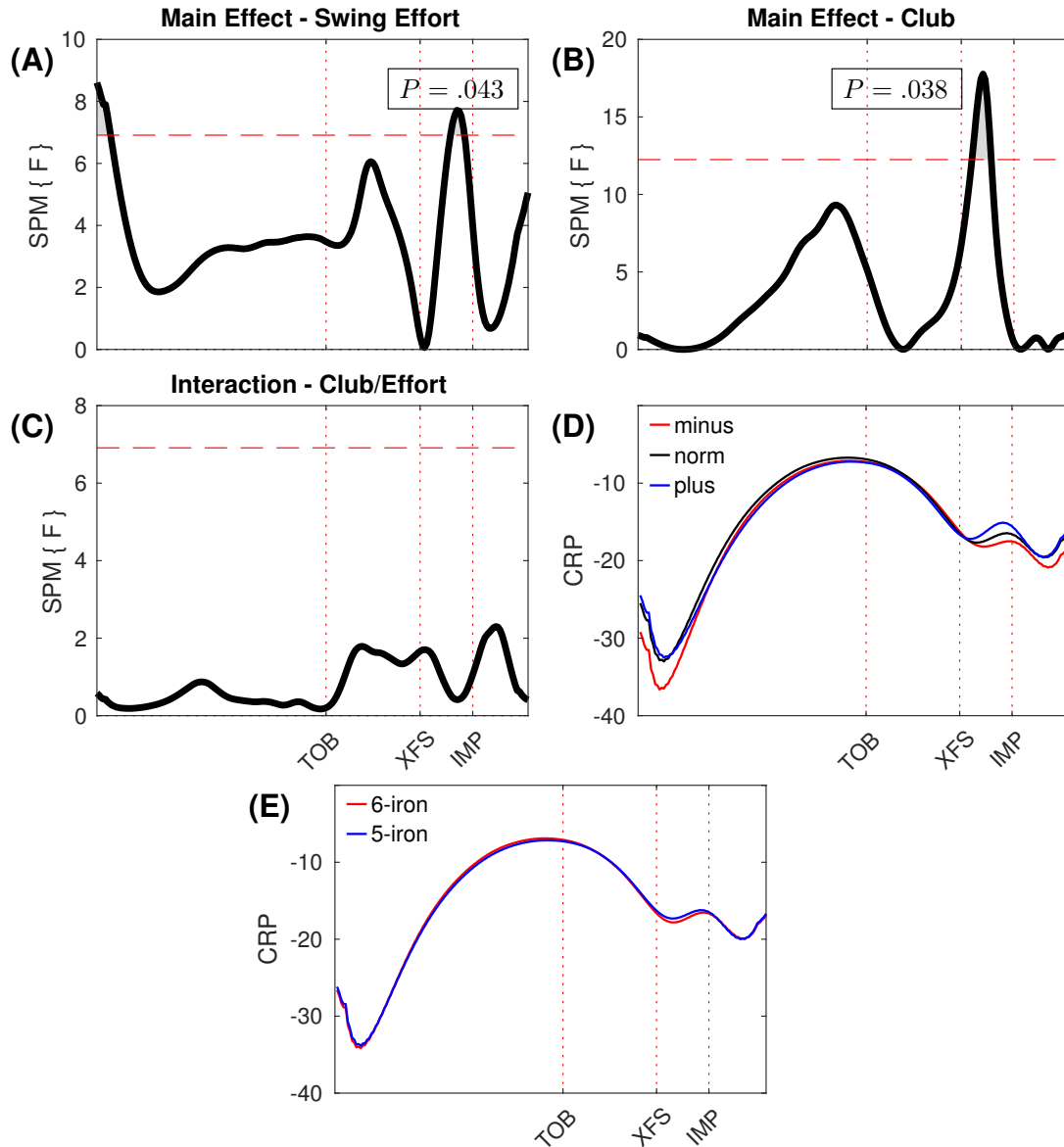
**Figure 3.** CRP curves for all participants. Blue lines show mean curves for the ‘plus’ swing effort condition, black shows ‘norm’ and red shows ‘minus’. Vertical dashed lines represent the average swing events: top of backswing (TOB), instant when pelvis and thorax separation is maximised in the downswing (XFS) and ball impact (IMP).

15 of the 16 participants; one participant had three missing trials and SPM repeated measures ANOVA is not yet implemented for unbalanced designs. The SPM two-way repeated measures ANOVA showed small, but significant main effects in the CRP time-series for swing effort and club. Figure 4 shows that CRP differed significantly between swing effort conditions and clubs late in the downswing: after the average X-factor stretch event and before ball impact. There was also a difference at the start and end of the swing for swing effort, which is most likely error due to the Gibbs phenomenon, seen by the jagged appearance of the CRP curves at the start and end of the signal (Huang et al., 1998). However, the focus of the analysis is on the downswing, so we ignored differences occurring in the first or last few frames.

### 3.4. Individual CRP

Seven out of the sixteen participants showed significant differences in CRP between swing effort conditions in the early downswing (between top of backswing and X-factor stretch; P2, P3, P5, P8, P9, P14, P16). Eleven of the sixteen participants showed differences in CRP in the late downswing (X-factor stretch to ball impact; P2–5, P8–10, P12, P13, P15, P16). Six of the participants showed significant differences in the both the early and late downswing. Figure 5 shows the  $F(t)$  trajectory for the even numbered participants to exemplify the breadth of pelvis-thorax coupling changes with swing effort (see supplementary Figure A1 for odd numbered participants).

While the group analysis showed a significant main effect for club, on an individual basis only two participants showed a main effect for club, P5 and P10, and the effect was found in the downswing only for P10 (see supplementary Figures A2 and A3). None of the participants showed a significant interaction.

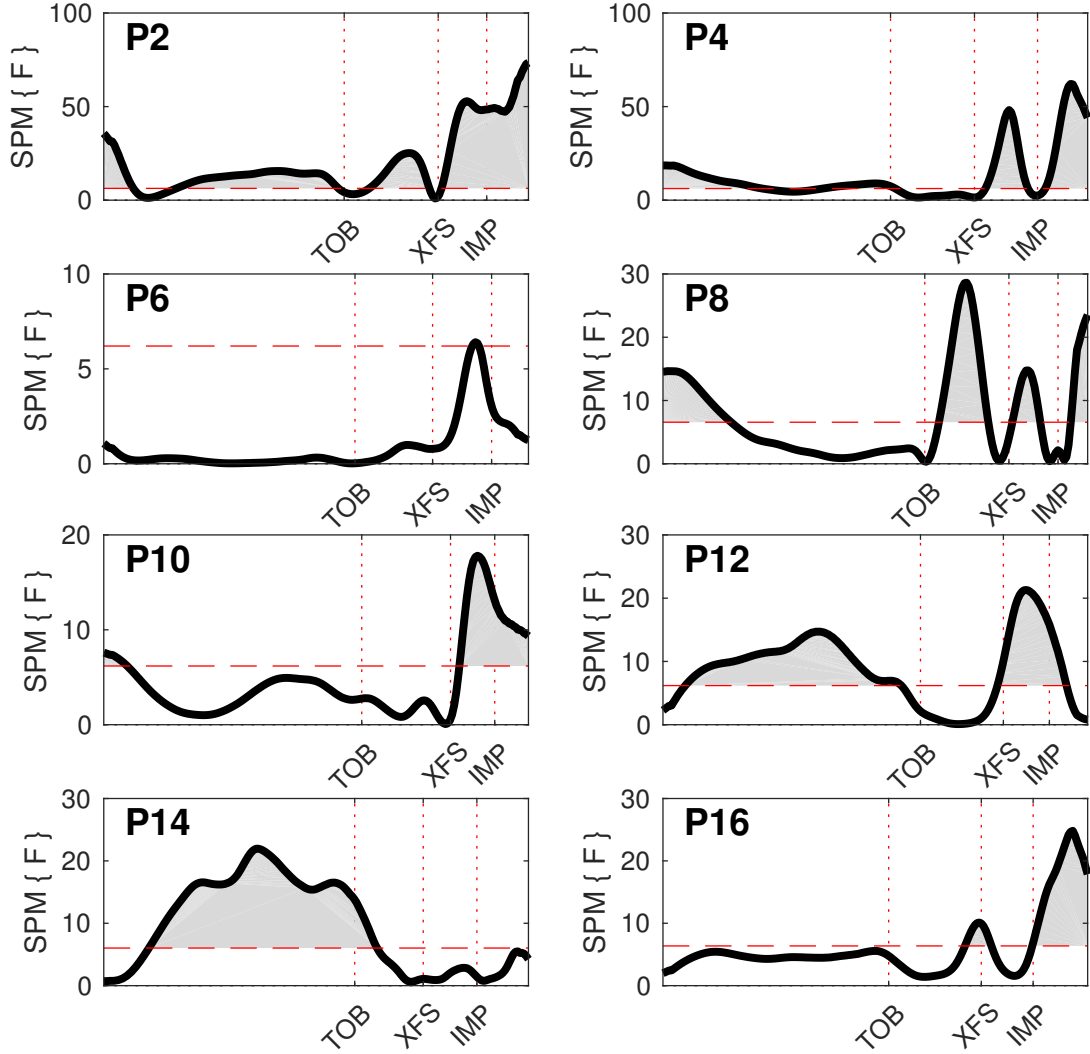


**Figure 4.**  $F(t)$  trajectory (black) and corresponding critical thresholds (horizontal red dashed) for (A) swing effort main effect, (B) club main effect and (C) club-swing effort interaction. Panel (D) shows the group means for pelvis-thorax CRP in each swing effort condition and (E) group CRP means for each club. Vertical dashed lines represent the average swing events: top of backswing (TOB), instant when pelvis and thorax separation is maximised in the downswing (XFS) and ball impact (IMP). Blue lines show mean curves for the ‘plus’ swing effort condition, black shows ‘norm’ and red shows ‘minus’.

#### 4. Discussion

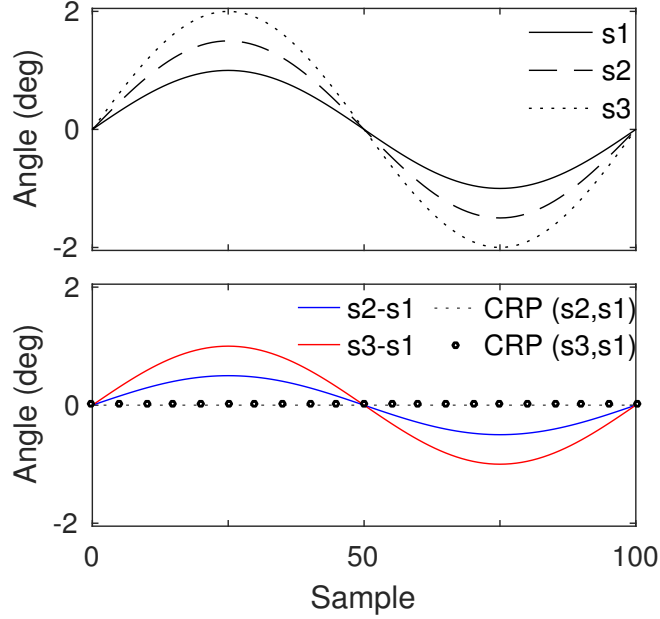
Several studies have implicated X-factor, and more strongly X-factor stretch, in maximising clubhead speed (Brown et al., 2011; Cheetham et al., 2001); regression models of large groups of golfers have also shown an association between X-factor and clubhead speed (Chu et al., 2010; Myers et al., 2008). However, in these cases, X-factor and X-factor stretch are characteristics of the study participants. Therefore, it is not clear whether swing speed can be modulated by pelvis-thorax coordination – just that golfers who tend to swing faster utilise similar kinematic principles.





**Figure 5.**  $F(t)$  trajectories for swing effort main effect for even numbered participants (participant number shown in top left of each panel). Odd numbered participants are available as supplementary material.

The task in the current study differed from many studies of X-factor, which typically look at maximal club or ball speed. The current study had participants scale their comfortable distance up and down by half club intervals so that we could investigate the change in pelvis and thorax kinematics, if any. With respect to angular separation between pelvis and thorax, we found that while X-factor did not change significantly with swing effort or club changes, X-factor stretch did for both. These findings are similar to those of Meister et al. (2011) who found differences in peak X-factor (defined the same as X-factor stretch in the current study) between three comparable swing efforts for 5-iron shots. We note the authors left it up to the participants to decide what ‘easy’, ‘medium’, and ‘hard’ swings were, and may not correspond exactly to the ‘minus’, ‘normal’ and ‘plus’ conditions of the current study. We also note the inter-individual variability in the timing of the X-factor stretch event in the down-swing (shown in Figure 3), which indicates that the participants in the current study achieve their X-factor stretch positions through different pelvis and thorax dynamics, given the differences in timing, angular displacement and angular velocity. Pataky,



**Figure 6.** Synthetic signals to compare angular separation and CRP. Top: three sinusoidal signals with varying amplitude. Bottom: Angular separation with respect to  $s_1$ . CRP is constant and zero as changes in amplitude do not affect CRP.

Vanrenterghem, and Robinson (2016) have suggested that biomechanical studies often extract discrete variables for convenience rather than for theoretically justified reasons, and that hypothesis testing using methods such as SPM are recommended to ensure meaningful analyses. Furthermore, CRP allows one to characterise the state of coordination between the pelvis and thorax in the downswing and promotes an understanding of the dynamics of their coupling. As suggested by Lamoth, Beek, and Meijer (2002), coordination measures are more suitable in assessing quality of movement than kinematic measures relating to individual segments. To demonstrate the difference between angular separation and CRP, Figure 6 shows synthetic cyclic signals varying in amplitude (top panel), their corresponding ‘angular’ separation as well as CRP (bottom panel). While differences in relative amplitude obviously lead to differences in separation – as in pelvis and thorax angular displacement in the golf swing – they do not necessarily lead to differences in CRP. In Figure 6, CRP is equal to zero for the entire time series because the signals’ phases do not change relative to each other. Therefore, CRP provides higher-order information that can help us understand the dynamics leading up to key events in the golf swing.

Comparing the CRP curves more closely to the results of Meister et al. (2011) provides insight into the role of pelvis-thorax coupling and the initiation of the stretch shortening cycle. Meister et al. (2011) found that peak X-factor (X-factor stretch in the current study) occurred just before the peak free moment, which may correspond to core muscles such as the external abdominal obliques contracting to accelerate axial thorax rotation (McHardy & Pollard, 2005). For the thorax to accelerate axially the pelvis must stabilise against its motion, which would result in an increase in the free moment. In general, nearly every golfer in the current study showed a change in CRP slope from negative to positive just after the X-factor stretch event (Figure 3). This shows that the core muscles must have increased tension as a result of the stretch and consequently contracted allowing the thorax to partially ‘catch up’ to the pelvis

in phase space. This is also inline with most descriptions of the proximal to distal kinematic sequence in the golf swing (see Lamb & Glazier, 2017, for a review). The predominantly non-significant differences for club are not surprising given the relatively small differences in club length and weight, compared to the difference between 5-iron and driver (Joyce, Burnett, Cochrane, & Ball, 2013).

#### 4.1. *Inter-individual variability*

The individual CRP analysis showed that for swing effort nearly every golfer showed a significant change in CRP. More specifically, at the point in the downswing when the thorax starts to catch up to the pelvis in phase space, the catch up is more prominent as swing effort increases. Only two golfers showed contradictory behaviours (P12 and P16 in Figure 3; P7 was unique). The shape of the CRP curves and the timing of the change in CRP slope from negative to positive, however, was variable between golfers and is in agreement with many other studies on golf swing biomechanics (see Glazier & Lamb, 2017, for a review). We speculate that the differences between golfers may be linked to functional musculoskeletal differences, such as muscle strength, limb length or rotational inertia, rather than conscious strategies to modify their swing technique. For example, gluteal activation is strongly linked to pelvis rotation and stabilisation in the golf swing (Donatelli, Dimond, & Holland, 2012) and may represent an important difference between the participants in the current study. Similarly, Oliver and Keeley (2010) showed that baseball pitchers' ability to activate the gluteal muscle group had a strong effect on hip and pelvis kinematics. Further research into the role of gluteal activation in pelvis-thorax coordination of the golf swing is needed to substantiate these speculations.

#### 4.2. *Summary*

This study showed that pelvis-thorax coupling in the downswing changed according to swing effort. We used CRP to characterise the dynamics of the pelvis-thorax coupling; since CRP is a relatively new measure in golf swing biomechanics we used SPM to determine the time point(s) in the swing at which changes occurred. There were substantial inter-individual differences in pelvis-thorax angular separation events – we, therefore, focussed on individual analyses. All but two participants showed a change in CRP slope from negative to positive in the late downswing, which we interpreted as the kinematic effect of the stretch shortening cycle. While most participants' kinematics generally followed this principle, the specifics were fairly unique to each individual. We speculated that functional musculoskeletal differences may be partially responsible to some extent for the differences between individuals but further research is needed for clarification.

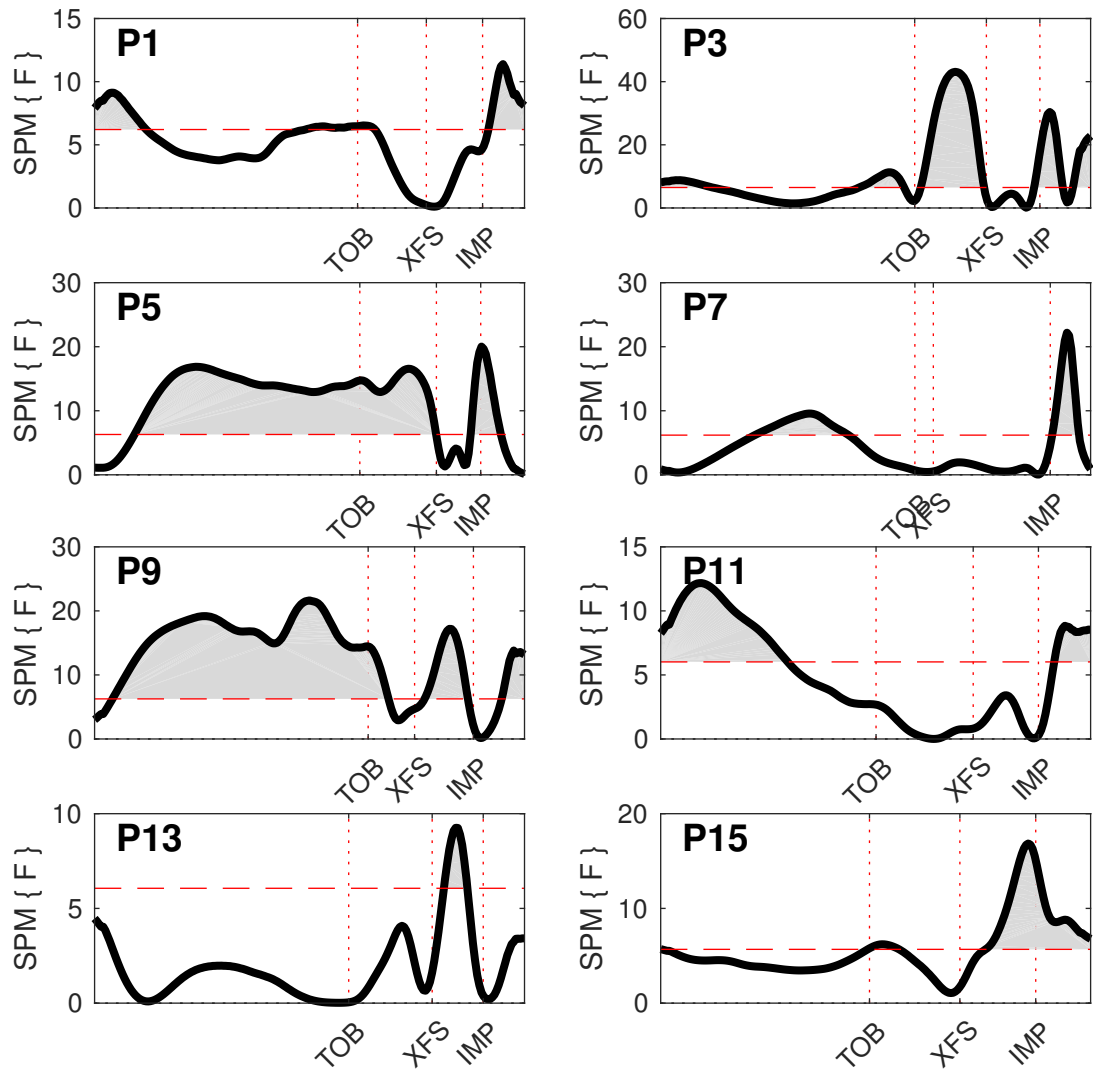
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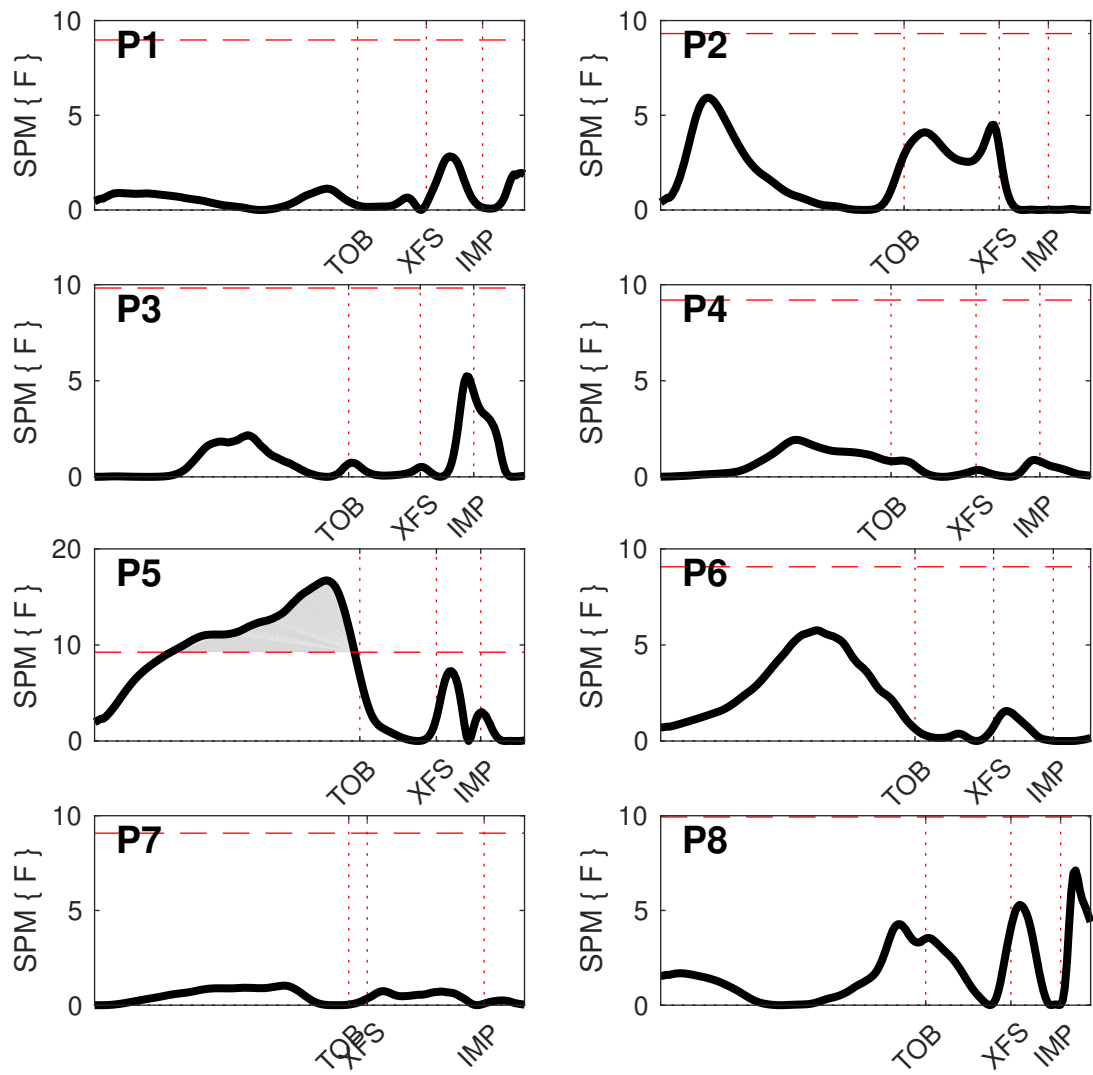
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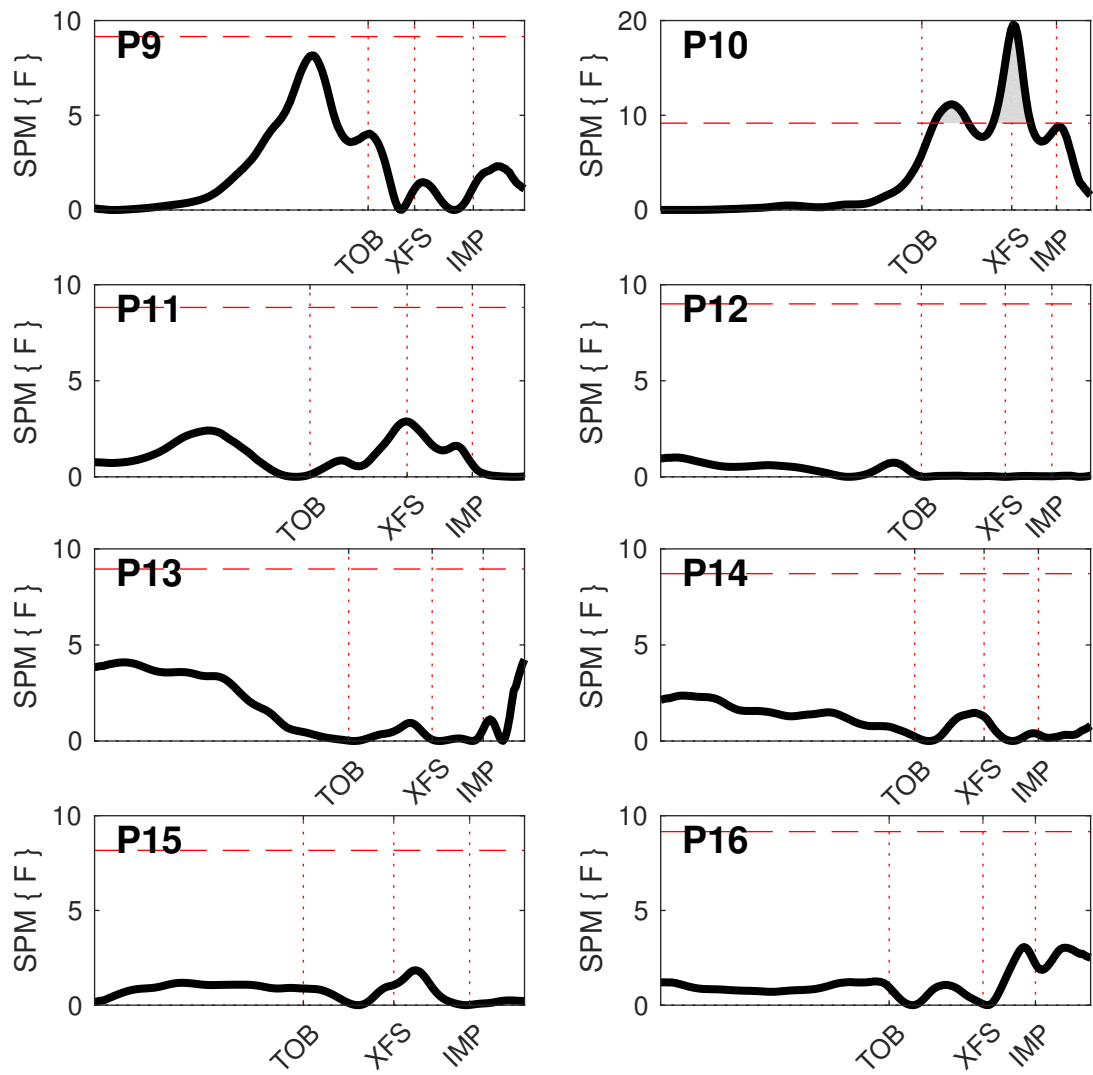
Appendix A. Supplementary Material



**Figure A1.**  $F(t)$  trajectories for swing effort main effect for odd numbered participants (participant number shown in top left of each panel).



**Figure A2.**  $F(t)$  trajectories for club main effect for participants 1–8 (participant number shown in top left of each panel).



**Figure A3.**  $F(t)$  trajectories for club main effect for participants 9-16 (participant number shown in top left of each panel).