2017

The most important "factor" in producing clubhead speed in golf

C Joyce
The University of Notre Dame Australia, chris.joyce@nd.edu.au

This article was originally published as:
Joyce, C. (2017). The most important "factor" in producing clubhead speed in golf. *Human Movement Science, 55*, 138-144.

Original article available here:
https://doi.org/10.1016/j.humov.2017.08.007

Joyce, C. (2017). The most important “factor” in producing clubhead speed in golf. *Human Movement Science, 55.* doi: 10.1016/j.humov.2017.08.007

The Most Important "Factor" in Producing Clubhead Speed in Golf

Christopher Joyce[1]

[1] School of Health Sciences, The University of Notre Dame Australia, Fremantle, Western Australia

Running Title: faster clubhead speed with x-factor and crunch-factor

Author Contact: chris.joyce@nd.edu.au [+61 (8) 94330224]

Word Count: 4018 (not including abstract or references)

Abstract Word Count: 224

Tables: Two

Figures: One

Abstract

Substantial experiential research into x-factor, and to a lesser extent crunch-factor has been undertaken with the aim of increasing clubhead speed. However, a direct comparison of the golf swing kinematics associated with each 'factor' has not, and possible differences when using a driver compared to an iron. Fifteen low handicap male golfers who displayed a modern swing had their golf swing kinematic data measured when hitting their own driver and five-iron, using a 10-camera motion analysis system operating at 250 Hz. Clubhead speed was collected using a validated launch monitor. No between-club differences in x-factor and crunch-factor existed. Correlation analyses revealed within-club segment (trunk and lower trunk) interaction was different for the driver, compared to the five-iron, and that a greater number of kinematic variables associated with x-factor, compared to crunch-factor were shown to be correlated with faster clubhead speeds. This was further explained in the five-iron regression model, where a significant amount of variance in clubhead speed was associated with increased lower trunk x-factor stretch, and reduced trunk lateral bending. Given that greens in regulation was shown to be the strongest correlated variable with PGA Tour earnings (1990-2004), the findings suggests a link to player performance for approach shots. These findings support other empiric research into the importance of x-factor as well as anecdotal evidence on how crunch-factor can negatively affect clubhead speed.

Key Words: golf, 3D, x-factor, crunch-factor, clubhead speed

1. Introduction

Skilled golfers who produce faster clubhead speeds produce longer hitting distances (Fletcher & Hartwell, 2004), which is an advantage when hitting both drivers and irons, providing accuracy is maintained (Wiseman & Chatterjee, 2006). However, the associated kinematics required to produce faster clubhead speeds have produced dissimilar findings when considering performance enhancement and the potential for injury. With the majority of experimental research into biomechanical performance using the driver (Myers et al., 2008; Chu, Sell, & Lephart, 2010; Cole & Grimshaw, 2014), it is therefore important that the biomechanical performance of irons used to reach greens are investigated, as greens in regulation (number of greens reached in regulation divided by the number of holes played) has been shown to be the strongest correlated component with PGA Tour earnings (r = -0.732) between 1990 and 1994, over putting average (r = 0.631) and driving distance (r = -0.231) (Wiseman & Chatterjee, 2006).

One of the most commonly investigated kinematic performance measures in golf is the ‘x-factor’ (Cheetham, Martin, & Motram, 2001; Myers et al., 2008; Kwon, Han, Como, lee, & Singhal, 2013). This refers to the amount of trunk axial rotation at the top of the backswing and is measured as the angular displacement between the shoulders and the pelvis (Myers et al., 2008; Brown, Selbie, & Wallace, 2013). It has been reported experimentally that skilled golfers who can attain a large x-factor at the top of the backswing are said to increase clubhead speed, and or ball velocity at ball impact (Cheetham et al., 2001; Myers et al., 2008; Chu et al., 2010). Additionally, whilst the shoulders remain static momentarily at the commencement of the downswing, the pelvis rotates towards the target and produces ‘x-factor stretch’ (Burden, Grimshaw, & Wallace, 1998; Cheetham et al., 2001). This is thought to facilitate a muscular elastic recoil effect from which faster clubhead speeds can be attained (Cheetham et al., 2001). These kinematics are observed in ‘modern’ swing golfers who utilise a greater shoulder turn, and keep the pelvis restricted throughout the backswing (Gluck, Bendo, & Spivak, 2007). The application of x-factor to other sports has been investigated by Lees & Nolan (2002), who reported faster kicking speeds in elite male footballers who exhibited increased shoulder and pelvis angular displacement.

Skilled golfers who utilise the x-factor at the top of the backswing to maximise trunk axial rotation velocity at ball impact also combine this with lateral bending of the trunk to the trailing side, as it is thought to apply a greater amount of force to the golf ball (Gluck et al., 2007; Chu et al., 2010). The product of trunk lateral bending and axial rotation velocity at ball impact is referred to as the 'crunch-factor', which is maximised around ball impact and the early stages of the follow-through (Morgan, Sugaya, Banks, & Cook, 1997; Sugaya, Tsuchiya, Morgan, & Banks, 1999; Gluck et al., 2007). Crunch-factor has also been suggested (although not directly measured) to occur in cricket bowling, with peak crunch-factor occurring at front-foot impact, shortly before ball release (Glazier, 2010). Empiric research into crunch-factor is limited. Increased trunk lateral bending velocity has been observed for skilled golfers hitting a mid-iron compared to that of a driver however, crunch-factor itself was not considered (Lindsay, Horton, & Paley, 2002).

It has been reported that excessive crunch-factor has the potential for injury in the vertebral body and facet joint of the lumbar spine (Gluck et al., 2007), as excessive trunk lateral bending restricts trunk axial rotation velocity during the downswing, and from a performance point of view, trunk axial rotation velocity is more important for skilled golfers aiming to maximise clubhead speed (Chu et al., 2010; Sato, Kenny & Dale, 2013). Combined segment postures during trunk movement have shown greater and more variable elecromyographic muscle activation patterns when undergoing trunk lateral bending and axial rotation, compared to that of trunk flexion and extension (Nairn & Drake, 2014; Schinkel-Ivy & Drake, 2015). Therefore, the importance of reducing muscle activation variability of the abdominal musculature to increase trunk stiffness and stability when undergoing movements specific to the golf swing is key for producing clubhead speed (Schinkel-Ivy & Drake, 2015; Glofcheski & Brown, 2017).

A substantial amount of empiric research exists for x-factor, when compared to crunch-factor. Recent developments in three dimensional motion analysis techniques have seen the trunk modelled as multiple segments (trunk and lower trunk), making crunch-factor more anatomically meaningful (Joyce, Burnett, & Ball, 2010; Brown et al., 2013; Cole & Grimshaw, 2014), and also allowing the investigation of segment interaction which has shown to be important in producing clubhead speed (Tinmark, Hellstrom, Halvorsen, & Thorstensson, 2010; Horan & Kavanagh, 2012). A direct comparison of the golf swing kinematic variables associated with each 'factor' has not, therefore it is unknown if there are between-club differences in x-factor and crunch-factor, when using a driver compared to an iron. Further, it has been recommended that future research be undertaken to assess the between-club differences in crunch-factor profiles, as it has been hypothesised that the different kinematic profiles of driver and iron swings previously observed (Egret, Vincent, Weber, Dujardin, & Chollet, 2003; Joyce, Burnett, Ball, & Cochrane, 2013) will have a greater emphasis on trunk lateral bending, than that of axial rotation velocity (Cole & Grimshaw, 2014). Finally, it is unknown which golf swing kinematic variables associated with each 'factor' are more important in producing faster clubhead speed. Therefore, the aims of this study were to firstly, determine the between-club (driver and five-iron) differences in x-factor and crunch-factor. Secondly, investigate the within-club segment interaction (trunk and lower trunk) for x-factor and crunch-factor, and if more x-factor or crunch-factor variables are related to clubhead speed. Thirdly, to better understand the different movement strategies of low handicap male golfers, which x-factor and crunch-factor variables are associated with faster clubhead speed for each club.

2. Methods

2.1 Participants & Experimental Protocol

Fifteen right-handed low handicap male golfers (mean ± SD: age = 22.7 ± 4.3 years, registered golfing handicap = 2.5 ± 1.9) were available for this study. A modified Nordic Low Back Pain questionnaire (Kuorinka et al., 1987) was completed by each participant to confirm the absence of back pain within the last 12 months. This was undertaken to ensure that each participant's full range of motion during their golf swing was not inhibited (Hosea & Gatt, 1996). All participants also underwent a qualitative golf swing video analysis to assess whether they demonstrated a “modern”, rather than “classic” golf swing (Gluck et al., 2007). This was performed by two Australian professional Golfers Association teaching professionals who independently verified “modern” golf swing traits. Those participants who exhibited golf swing traits associated with a “classic” golf swing, i.e., heel raise and excessive pelvic movement were excluded from the study. On the basis of these criteria, this resulted in 5 of the originally screened 20 participants being excluded.

After a standardised 5 minute warmup consisting of practice and real swings, each participant hit five shots with their own driver, followed by their own five-iron, using the same leading brand of golf ball. Participants were instructed to hit the golf ball as straight as possible using their normal, full swing. During testing, participants wore bicycle shorts, their own golf glove and golf shoes, and hit off a tee positioned on an artificial turf surface into a net positioned 5 m in front of the hitting area. Trials were disregarded if the launch monitor failed to record clubhead speed, swings resulted in inaccurate shots (balls landing outside of a predicted 37 m wide fairway as determined by the launch monitor), or if the participant felt that improper contact was made with the ball. This study was undertaken in an indoor biomechanics laboratory. Ethical approval to conduct the study was provided by the Institutional Human Research Ethics Committee.

2.2 Data Collection

A 10-camera MX-F20 Vicon-Peak Motion Analysis system (Oxford Metrics, Oxford, UK) operating at 250 Hz was used to capture each participant’s 3D golf swing kinematics. A previously validated multi-segment trunk model (Joyce et al., 2010) was used to create three anatomical reference frames for the trunk, lower trunk and pelvis. For the required golf swing kinematics, two events were identified during the golf swing. The top of the backswing was defined as the frame where the two club markers changed direction to initiate the downswing (Lephart, Smoliga, Myers, Sell, & Tsai, 2007). A small piece of retro-reflective tape attached to the golf ball was used to identify ball impact. Ball impact was defined as the frame immediately before the ball was first seen to move after contact with the driver (Joyce et al., 2013). Clubhead speed at the point of ball impact was collected using a validated real-time launch monitor (PureLaunch™, Zelocity, USA) which was positioned at a distance of 3 m, aiming perpendicular to the participant’s target line (Joyce, Burnett, Herbert, & Reyes, 2014).

2.3 Data Analysis

From the five trials recorded for each club, the trials with the fastest and slowest clubhead speed were removed, and the remaining three trials were averaged, assuming that there was minimal retro-reflective marker drop out, the ball landed within a predicted 37 m wide fairway (from the launch monitor), and where the participant felt that proper contact had been made, were analysed. All golf swing kinematics were smoothed using a Woltring filter with a mean square error of 20 mm^2 (Woltring, 1986).

The multi-segment model used in this study was developed in Vicon BodyBuilder V.3.6.1 (Oxford, UK) and used in Vicon Nexus V.1.7.1 (Oxford, UK) to obtain all kinematic variables (as described below). Cardan angles reported for the trunk were reduced from the joint coordinate system of the shoulders relative to the joint coordinate system of the pelvis, and lower trunk Cardan angles reduced from the joint coordinate system of the lower thorax relative to the joint coordinate system of the pelvis (i.e., 0,0,0 indicates the shoulder or lower thorax reference frame is relative to the pelvis reference frame). In order to calculate the rotations relative to the pelvis, Cardan angles for each segment were reported using a ZYX (lateral bending, flexion/extension, axial rotation) order of rotation, followed by derivation of axial rotation velocity using finite difference calculations. X-factor of the trunk was determined at the top of the backswing as the relative angle (axial rotation – X) between the trunk and pelvis segments. Lower trunk x-factor was determined at this point also, as the relative angle (axial rotation – X) between the lower trunk and pelvis segments. Crunch-factor of both the trunk and lower trunk segments was calculated as the product of lateral bending and axial rotation velocity, reported as $\text{rads}^2 \cdot \text{s}^{-1}$. With previous research (Morgan et al., 1997) and pilot work in this study indicating that the crunch-factor is maximised at ball impact, lateral bending and axial rotation velocity of the trunk and lower trunk, as well as clubhead speed form the launch monitor, were determined at this point.

Six golf swing kinematic variables obtained from the trunk and lower trunk segments, as well as clubhead speed from the launch monitor, were analysed in this study (see Table 1). The ensemble averages for both x-factor and crunch-factor of each segment and for each club between the top of the backswing (0%) and ball impact (100%) were created (see Figure 1). All data were time normalised using cubic spline interpolation, so that all analysed participant golf swings were time-matched.

2.4 Statistical Analysis

All statistical analyses were performed using SPSS V22.0 for Windows (IBM Co., NY, USA). All data were screened to assess normality using histogram, box and whisker, and Q-Q plots. Box and whisker plots identified 2% all variables as outliers although, these were all within 1.5 standard deviations of the mean, resulting in no missing values, extreme outlier cases, or multivariate outliers. Descriptive data were reported as mean and standard deviation with standard error, for golf swing kinematic variables and clubhead speed. For the first aim, a dependent t-test was conducted to assess between-club differences in golf swing kinematics and clubhead speed, with a Bonferroni adjustment of the p value made to correct the family-wise error rate ($p \leq .0038$). For the second aim, Pearson product-moment correlation analyses were performed to investigate the within-club segment interaction (trunk and lower trunk) for x-factor and crunch-factor, and if more x-factor or crunch-factor kinematic variables were related to clubhead speed. Pearson correlation coefficient values between 0.2 and 0.4 were considered as weak associations, values between 0.4 and 0.7 were considered as moderate and values above 0.7 as strong (Johnson, 2000). For the third aim, a forward linear regression model was generated for each club. All golf swing kinematic variables were entered into each model as independent variables, with clubhead speed entered as the dependent variable. Each model reported the highest significant ($p < .05$) amount of variance associated with faster clubhead speeds, with assumptions of normality, linearity, homoscedasticity, and independence of residuals met.

3. Results

3.1 Between-club differences in x-factor and crunch-factor

For the first aim, dependent t-tests revealed no significant ($p \leq .0038$) between-club differences in x-factor and crunch-factor variables (Table 1), indicating similar golf swing kinematics, irrespective of club.

INSERT TABLE 1 ABOUT HERE

INSERT FIGURE 1 ABOUT HERE

3.2 X-factor and crunch-factor variables correlated with clubhead speed

For the second aim, within-club segment interaction (trunk and lower trunk) found that trunk and lower trunk x-factor ($r = .84$, $p <.01$) and x-factor stretch ($r = .71$, $p = .01$) were correlated for the five-iron but not the driver. Trunk and lower trunk crunch-factor was correlated for both the driver ($r = .66$, $p = .01$) and the five-iron ($r = .52$, $p = .05$). Further, a greater number of x-factor variables were correlated to clubhead speed for both clubs (particularly the five-iron), than crunch-factor variables. For the driver, there was a moderate correlation between lower trunk axial rotation at ball impact and clubhead speed ($r = .45$, $p = .01$). A greater amount of x-factor variables (four) than crunch-factor variables (one) were reported for the five-iron. There was a strong correlation between lower trunk x-factor stretch and clubhead speed ($r = .78$, $p < .01$). There were moderate correlations for lower trunk x-factor ($r = .66$, $p = .01$), lower trunk segment velocity at ball impact ($r = .53$, $p = .04$), and trunk x-factor stretch and clubhead speed ($r = .52$, $p = .05$). There was a single moderate correlation for the crunch-factor variable, trunk lateral bending at ball impact and clubhead speed ($r = -.61$, $p = .02$). However, the negative correlation shows that increased trunk lateral bending at ball impact is correlated with slower clubhead speeds.

3.3 Driver and five-iron regression models

For the third aim, there was a non-significant regression model for the driver. Modifying the *p* value entry level to $p < .10$, allowed a single variable, lower trunk axial rotation at ball impact, to explain a non-significant 20% of variance in faster clubhead speeds. There was a significant ($p < .05$) regression model for the five-iron, with 74% of variance in clubhead speed explained by lower trunk x-factor stretch, and trunk lateral bending at ball impact. However, as seen in the correlations of the second aim, trunk lateral bending at ball impact had a negative beta coefficient, meaning faster clubhead speeds were associated with a decreased amount of trunk lateral bending at ball impact.

INSERT TABLE 2 ABOUT HERE

4. Discussion

Results for the first aim of this study revealed no significant ($p < .0038$) between-club differences in golf swing kinematics. Axial rotation variables of the trunk and lower trunk (see Table 1) were similar when hitting a driver and five-iron, along with axial rotation velocity, the other crunch-factor variable, and lateral bending towards the trailing side of the trunk and lower trunk. Clubhead speed averaged 3 $m \cdot s^{-1}$ faster for the driver when compared to the five-iron, but was not significant at the $p < .0038$ level. Egret et al. (2003), had reported a slightly larger, yet significant ($p < .05$) x-factor for the driver compared with the five-iron although, recent evidence suggests that certain methods used to measure x-factor are questionable based on the motion analysis techniques used (Kwon et al., 2013). As used in this study, more anatomically valid x-factor can be obtained when modelling the thorax as multi-segments (upper and lower, relative to the pelvis) to suit the rotational characteristics of the spine, and using Cardan / Euler 3D methods as opposed to projected plane methods (Brown et al., 2013; Kwon et al., 2013).

The second aim of this study was to investigate the within-club segment interaction (trunk and lower trunk) for x-factor and crunch-factor, and if a greater number of kinematic variables associated with x-factor or crunch-factor were correlated with faster clubhead speeds. Both trunk and lower trunk correlations for x-factor and x-factor stretch were found for the five-iron, but not the driver indicating that traits of a modern golf swing for the driver where a greater shoulder turn and restricted pelvis is seen throughout the backswing (Gluck et al., 2007). Segment interaction may then be different for the five-iron where it is possible that shot accuracy is more important than maximising hitting distance, and x-factor of the trunk is less than the driver, and similar to that of the lower trunk. Although not significant, x-factor and x-factor stretch for the five-iron were less than that of the driver. However, trunk and lower trunk correlations for crunch-factor were present for both the driver and five-iron indicating similar segment interaction. This supports the suggestion that analysing crunch-factor in the lower trunk is more anatomically meaningful (Cole & Grimshaw, 2014), and further strengthens the Cardan / Euler 3D methods used in this study (Brown et al., 2013; Kwon et al., 2013). Following this, Pearson correlations for the driver reported a single x-factor variable, lower trunk axial rotation at ball impact to be moderately correlated with clubhead speed. This would suggest lower trunk clearance (increased segment axial rotation) through impact allows the more distal segments in the kinetic chain, such as the arms, hands and golf club to progress. The interaction of multiple trunk segments, through proximal to distal segment sequencing has been shown to be important in producing clubhead velocity (Tinmark et al., 2010; Horan & Kavanagh, 2012).

Correlations for the five-iron revealed four x-factor variables that were moderately correlated with clubhead speed, with lower trunk x-factor stretch reporting a strong correlation. This is thought to facilitate a muscular elastic recoil effect from which faster clubhead speeds can be attained (Cheetham et al., 2001). The other x-factor variables reported agree with similar experimental research, that trunk x-factor stretch and lower trunk x-factor were all found to be correlated with clubhead speed (Myers et al., 2008; Chu et al., 2010; Joyce et al., 2013). Lower trunk velocity at ball impact was the fourth x-factor variable that was correlated with clubhead speed. Further analysis revealed that this variable was also moderately correlated with both lower trunk x-factor ($r = .67$, $p = .01$) and lower trunk x-factor stretch ($r = .65$, $p = .01$). The single crunch-factor variable correlated with clubhead speed was trunk lateral bending at ball impact. The greater amount of x-factor variables reported for the five-iron support the idea that x-factor variables are more strongly correlated to clubhead speed than crunch-factor variables. With respect to golf, evidence suggests that excessive trunk lateral bending restricts trunk axial rotation velocity during the downswing, and axial rotation velocity is more important when aiming to maximise clubhead speed (Chu et al., 2010; Sato et al., 2013, Cole & Grimshaw, 2014). Increased muscle activation pattern variability has been shown in combined lateral bending and axial rotation trunk postures (Nairn & Drake, 2014; Schinkel-Ivy & Drake, 2015). By reducing trunk postures associated with lateral bending, the reduced muscle activation pattern variability assists in stiffening and stabilising the trunk more efficiently when undergoing movements specific to the golf swing (Schinkel-Ivy & Drake, 2015; Glofcheski & Brown, 2017).

For the final aim of this study, a non-significant forward linear regression model was reported for the driver. Modifying the p value entry level to $p <.10$, allowed a single variable, lower trunk axial rotation at ball impact to explain a non-significant 20% variance in clubhead speed. This variable was reported by Meister et al. (2011), as explaining a similar amount of variability (19%), to support the lower trunk moving through ball impact to support proximal to distal sequencing in the golf swing. Results for the first aim indicated similar golf swings, irrespective of club. Therefore, as participants used their own driver and five-iron, the greater modifiable properties that modern-day drivers possess over irons (i.e.

shaft flex) may be responsible for the low amount of variance explained (Hocknell, 2002; Osis & Stefanyshyn, 2012). The interaction between participant and their driver in terms of ‘loading’ the shaft for maximising clubhead speed through wrist kinematics was not considered in this study although, this interaction for drivers fitted with shafts of different stiffness has reported differences in clubhead speed (Betzler, et al., 2012). The five-iron model accounted for a significant (p <.05) 74% of variance in faster clubhead speed, explained by lower trunk x-factor stretch, and trunk lateral bending at ball impact. The negative beta coefficient reported for trunk lateral bending supports previous findings that faster clubhead speed is produced when crunch-factor, through lateral bending, is minimised (Chu et al., 2010; Sato et al., 2013). Both models reported lower trunk involvement being important for producing clubhead speed. In the modern golf swing, pelvic movement at ball impact leads the trunk irrespective of club which leads to increased lateral bending of the trailing side (McHardy, Pollard, & Bayley, 2006). Although not significant at ball impact, trunk lateral bending was greater and trunk axial rotation velocity was slower for the five-iron which may have contributed to slower clubhead speed, compared to that of the driver.

The findings of this study should be considered along with some limitations. This study was limited to a highly-skilled homogenous cohort, with a fixed sample size of 15. The non-significant difference reported for the first aim may be due to a type II error (the probability of accepting a false null hypothesis) however, the homogenous cohort available would not show differences in their golf swings due to skill level, for x-factor and crunch-factor. This may have resulted in a non-significant amount of variance explained in the driver regression model. However, as the five-iron model explained a significant amount of variance in clubhead speed, it is possible that by allowing the participants to hit with their own drivers, the various modifiable properties modern day drivers possess over non-modifiable irons (Hocknell, 2002), as well as inter-participant variability of how they modified the kinematics of other body segment not measured in this study, such as wrist ‘release’ (radial to ulnar deviation), based on various different shaft profiles used (i.e. stiff and extra stiff) (Betzler, Monk, Wallace, & Otto, 2012; Osis & Stefanyshyn, 2012) may have explained the non-significant driver model. Conversely, allowing participants to hit with their own clubs allows familiarisation which is important for indoor testing (Kenny, Wallace, & Otto, 2008).

5. Conclusion

There were no between-club differences in the kinematic variables associated with x-factor and crunch-factor however, within-club segment (trunk and lower trunk) interaction was different for the five-iron, compared to the driver, and a greater number of kinematic variables associated with x-factor were shown to be correlated with faster clubhead speeds. This was further explained in the five-iron regression model, which revealed a significant amount of variance in clubhead speed to be associated with increased lower trunk x-factor stretch, and reduced crunch-factor through trunk lateral bending. In particular, the greater number of significant results reported for the five-iron strengthen the link to approach shots, with greens in regulation shown to be the strongest correlated variable with PGA Tour earnings (1990-2004). These findings support other empiric research into the importance of x-factor as well as anecdotal evidence on how crunch-factor can negatively affect clubhead speed.

Acknowledgments

The author would like to thank the Australian PGA for their assistance in participant recruitment for this study, and the Institute for Health Research at the University of Notre Dame Australia (Fremantle Campus) for their assistance with the research methods.

Tables & Figure

Table 1. Between-club golf swing kinematics and clubhead speed (Mean ± SD & SE).

Table 2. Between-club forward linear regression models explaining clubhead speed.

Figure 1. Ensemble averages (solid line) of x-factor and crunch-factor variables for the driver (left and five-iron (right) for all participants. Shaded areas represent one standard deviation from the mean. Data are shown for the trunk and lower trunk segments from the top of backswing (0%) to ball impact (100%).

References

Betzler, N., Monk, S., Wallace, E., & Otto, S. (2012). Effects of golf shaft stiffness on strain, clubhead presentation and wrist kinematics. *Sports Biomechanics, 11*(2), 223-238. http://dx.doi.org/10.1080/14763141.2012.681796

Brown, S. J., Selbie, W. S., & Wallace, E. S. (2013). The X-factor: An evaluation of common methods used to analyse major inter-segment kinematics during the golf swing. *Journal of Sports Sciences, 31*(11), 1156-1163. http://dx.doi.org/10.1080/02640414.2013.775474

Burden, A. M., Grimshaw, P. N., & Wallace, E. S. (1998). Hip and shoulder rotations during the golf swing of sub-10 handicap players. *Journal of Sports Sciences*, *16*(2), 165-176. http://dx.doi.org/10.1080/026404198366876

Cheetham, P., Martin, P., & Mottram, R. (2001). The importance of stretching the “X-factor” in the downswing of golf: The “X-factor stretch”. In P. R. Thomas (Ed.) *Optimising Performance in Golf*. (pp.192-199). Brisbane: Australian Academic Press Ltd.

Chu, Y., Sell, T. C., & Lephart, S. M. (2010). The relationship between biomechanical variables and driving performance during the golf swing. *Journal of Sports Sciences, 28*(11), 1251-1259. http://dx.doi.org/10.1080/02640414.2010.507249

Cole, M. H., & Grimshaw, P. N. (2014). The crunch factor’s role in golf-related low back pain. *The Spine Journal, 14*(5), 799-807. doi:10.1016/j.spinee.2013.09.019

Egret, C.I., Vincent, O., Weber, J., Dujardin, F.H., & Chollet, D. (2003). Analysis of 3D kinematics concerning three different clubs in golf swing. *International Journal of Sports Medicine, 24*(6), 465-470. https://doi.org/10.1055/s-2003-41175

Fletcher, I.M., & Hartwell, M. (2004). Effect of an 8-week combined weights and plyometric training program on golf drive performance. *Journal of Strength and Conditioning Research, 18*(1), 59-62. http://dx.doi.org/10.1519/00124278-200402000-00008

Glofcheskie, G., & Brown, S. (2017). Athletic background is related to superior trunk proprioceptive ability, postural control, and neuromuscular responses to sudden perturbations. *Human Movement Science, 52*, 74-83. http://dx.doi.org/10.1016/j.humov.2017.01.009

Glazier, P. (2010). Is the ‘crunch-factor’ an important consideration for the aetiology of lumbar spine pathology in cricket fast bowlers? *Sports Medicine, 40*(10), 809-815. doi:10.2165/11536590-000000000-00000

Gluck, G. S., Bendo, J. A., & Spivak, J. M. (2007). The lumbar spine and low back pain in golf: a literature review of swing biomechanics and injury prevention. *The Spine Journal, 8*(5), 1-11. http://dx.doi.org/10.1016/j.spinee.2007.07.388

Hocknell, A. (2002). High-performance driver design: Benefits for all golfers. *Journal of Sports Sciences, 20*(8), 643-649. https://doi.org/10.1080/026404102320183211

Horan, S. A., & Kavanagh, J. J. (2012). The control of upper body segment speed and velocity during the golf swing. *Sports Biomechanics, 11*(2), 165-174. http://dx.doi.org/10.1080/14763141.2011.638390

Hosea, T., & Gatt, C. (1996). Back pain in golf. *Clinics in Sports Medicine, 15*(1), 37-53.

Johnson, I. (2000). I’ll give you a definite maybe. *An introductory handbook on probability, statistics and Excel.* http://records.viu.ca/~johntoi/maybe/title.htm. Accessed 18.01.16

Joyce, C., Burnett, A. F., & Ball, K. (2010). Methodological considerations for the 3D measurement of the X-factor and lower trunk movement in golf. *Sports Biomechanics, 9*(3), 206-221. http://dx.doi.org/10.1080/14763141.2010.516446

Joyce, C., Burnett, A.F., Ball, K., & Cochrane, J. (2013). 3D trunk kinematics in golf: between-club differences and relationships to clubhead speed. *Sports Biomechanics, 12*, 108-120. doi:10.1080/14763141.2012.728244

Joyce, C., Burnett, A.F., Herbert, S., & Reyes, A. (2014). A dynamic evaluation of how kick point location influences swing parameters and related launch conditions. *Proceedings IMechE Part P: Journal of Sports Engineering & Technology, 228*, 111-119. http://dx.doi.org/10.1177/1754337113515469

Kenny, I.C., Wallace, E.S., & Otto, S.R. (2008). Influence of shaft length on golf driving performance. *Sports Biomechanics, 7*(3), 322-332. https://doi.org/10.1080/14763140802233249

Kuorinka, I., Jonsson, B., Kilbom, A., Vinterberg, H., Biering-Sorensen, F., Andersson, G., & Jorgensen, K. (1987). Standardised Nordic questionnaires for the analysis of musculoskeletal symptoms. *Applied Ergonomics, 18*(3), 233-237. http://dx.doi.org/10.1016/0003-6870(87)90010-X

Kwon, Y. H., Han, K. H., Como, C., Lee, S., & Singhal, K. (2013). Validity of the X-factor computation methods and relationship between the X-factor parameters and clubhead velocity in skilled golfers. *Sports Biomechanics, 12*(3), 231-246. http://dx.doi.org/10.1080/14763141.2013.771896

Lees, A., & Nolan, L. (2002). Three-dimensional kinematic analysis of the instep kick under speed and accuracy conditions. In. W. Spinks, T. Reilly & A. Murphy (Eds.), *Science and Football IV* (pp. 16-21). London: Routledge.

Lephart, S. M., Smoliga, J. M., Myers, J. B., Sell, T. C., & Tsai, Y. (2007). Eight-week golf-specific exercise program improves physical characteristics, swing mechanics, and golf performance in recreational golfers. *Journal of Strength and Conditioning Research, 21*(3), 860-869. http://dx.doi.org/10.1519/00124278-200708000-00036

Lindsay, D. M., Horton, J. F., & Paley, R. D. (2002). Trunk motion of male professional golfers using two different golf clubs. *Journal of Applied Biomechanics, 18*(4), 366-373. https://doi.org/10.1123/jab.18.4.366

McHardy, A., Pollard, H., & Bayley, G. (2006). A comparison of the modern and classic golf swing: a clinician's perspective. *South African Journal of Sports Medicine, 18*(3), 80-92. https://doi.org/10.17159/2078-516x/2006/v18i3a239

Meister, D.M., Ladd, A.L., Butler, E.E, et al. (2011). Rotational biomechanics of the elite golf swing: Benchmark for amateurs. *Journal of Applied Biomechanics, 27*(3), 242-251. doi:10.1123/jab.27.3.242

Morgan, D., Sugaya, H., Banks, S., & Cook, F. (1997). A new twist on golf kinematics and low back injuries: the crunch factor. In: Farrally, M.R., & Cochran, A.J. (Eds.), *Science and Golf III: Proceedings of the World Scientific Congress on Golf.* (pp. 120-126). Leeds, UK: Human Kinetics.

Myers, J., Lephart, S., Tsai, Y. S., Sell, T., Smoliga, J., & Jolly, J. (2008). The role of upper torso and pelvis rotation in driving performance during the golf swing. *Journal of Sport Sciences*, *26*(2), 181-188. http://dx.doi.org/10.1080/02640410701373543

Nairn, B., & Drake, J. (2014). Impact of lumbar spine postures on thoracic spine motion and muscle activation patterns. *Human Movement Science, 37,* 1-11. http://dx.doi.org/10.1016/j.humov.2014.06.003

Osis, S. T., & Stefanyshyn, D.J. (2012). Golf players exhibit changes to grip speed parameters during club release in response to changes in club stiffness. *Human Movement Science, 31,* 91-100. doi:10.1016/j.humov.2011.02.006

Sato, K., Kenny, I.C., & Dale, B.R (2013). Current golf performance literature and application to training. *Journal of Trainology, 2*(2), 23-32. https://doi.org/10.17338/trainology.2.2_23

Schinkel-Ivy, A., & Drake, J. (2015). Sequencing of superficial trunk muscle activation during range-of-motion tasks. *Human Movement Science, 43*, 67-77. http://dx.doi.org/10.1016/j.humov.2015.07.003

Sugaya, H., Tsuchiya, H., Morgan, D.A., & Banks, S.A. (1999). Low back injury in elite and professional golfers: and epidemiologic and radiographic study. In: Farrally, M.R., & Cochran, A.J. (Eds.), *Science and Golf III: Proceedings of the World Scientific Congress on Golf.* (pp. 83-91). Leeds, UK: Human Kinetics.

Tinmark, F., Hellstrom, J., Halvorsen, K., & Thorstensson, A. (2010).Elite golfers' kinematic sequence in full-swing and partial-swing shots. *Sports Biomechanics*, *9*(4), 236-244. https://doi.org/10.1080/14763141.2010.535842

Wiseman, F., & Chatterjee, S. (2006). Comprehensive analysis of golf performance on the PGA Tour: 1990-2004. *Perceptual and Motor Skills*, *102*(1), 109-117. https://doi.org/10.2466/pms.102.1.109-117

Woltring, H. J. (1986). A FORTRAN package for generalized, cross-validatory spline smoothing and differentiation. *Advanced Engineering Software, 8*(2), 104-113. https://doi.org/10.1016/0141-1195(86)90098-7