2016

Multi-segment trunk models used to investigate the crunch factor in golf and their relationship with selected swing and launch parameters

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

This article was originally published as:
Joyce, C. (2016). Multi-segment trunk models used to investigate the crunch factor in golf and their relationship with selected swing and launch parameters. *Journal of Sports Sciences,*.
http://doi.org/http://dx.doi.org/10.1080/02640414.2016.1149600
Original article available here:
http://www.tandfonline.com/doi/full/10.1080/02640414.2016.1149600

Christopher Joyce, Paola Chivers, Kimitake Sato & Angus Burnett (2016): Multi-segment trunk models used to investigate the crunch factor in golf and their relationship with selected swing and launch parameters, Journal of Sports Sciences, DOI: 10.1080/02640414.2016.1149600

To link to this article: http://dx.doi.org/10.1080/02640414.2016.1149600

Multi-segment trunk models used to investigate the crunch factor in golf and their relationship with selected swing and launch parameters

Journal:	*Journal of Sports Sciences*
Manuscript ID	RJSP-2015-0058.R2
Manuscript Type:	Original Manuscript
Keywords:	golf, crunch factor, clubhead speed

Multi-segment trunk models used to investigate the crunch factor in golf and their relationship with selected swing and launch parameters

Running Title: 3D crunch factor and golf performance

Key Words: golf, 3D, crunch factor, clubhead velocity, launch angle

Word Count: 3741 (not including references)

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

Abstract

The use of multi-segment trunk models to investigate the crunch factor in golf may be warranted. The first aim of the study was to investigate the relationship between the trunk and lower trunk for crunch factor related variables (trunk lateral bending and trunk axial rotation velocity). The second aim was to determine the level of association between crunch factor related variables with swing (clubhead velocity) and launch (launch angle). Thirty five high level amateur male golfers (Mean ± SD: age = 23.8 ± 2.1 years, registered golfing handicap = 5 ± 1.9) without low back pain had kinematic data collected from their golf swing using a 10-camera motion analysis system operating at 500 Hz. Clubhead velocity and launch angle were collected using a validated real-time launch monitor. A positive relationship was found between the trunk and lower trunk for axial rotation velocity ($r(35) = .47$, $p < .01$). Cross-correlation analysis revealed a strong coupling relationship for the crunch factor ($R^2 = 0.98$) between the trunk and lower trunk. Using generalised linear model analysis, it was evident that faster clubhead velocities and lower launch angles of the golf ball were related to reduced lateral bending of the lower trunk.

Introduction

Today's high level golfers focus on distance when hitting a driver from the tee (Gluck et al., 2007). This has seen a change from a 'classic' to a 'modern' golf swing, where greater axial rotation of the shoulders relative to the hips (also known as X-factor) is seen at the top of the backswing (Cheetham et al., 2001; McHardy et al., 2006; Gluck et al., 2007). It would seem logical that an increased X-factor at the top of the backswing, will lead to increased axial rotation velocity of the trunk, which will in turn, lead to greater clubhead velocity at ball impact (McLean, 1994; McHardy et al., 2006; Chu et al., 2010). Further, at the point of ball impact, an increase in lateral bending of a line connecting the shoulders relative to the pelvis (i.e. the trunk) on the trailing side is thought to increase the force applied behind the ball (Gluck et al., 2007; Chu et al., 2010). The product of lateral bending and axial rotation velocity is termed the 'crunch factor' (Gluck et al., 2007), and it is believed that this variable is maximised around ball impact and the early stages of follow through (Morgan et al., 1997; Sugaya et al., 1999). It could be argued that the crunch factor may have implications for both performance enhancement and the causation of low back pain.

Investigations have reported dissimilar findings on the relationship between crunch factor and low back pain (Sugaya et al., 1999; Lindsay & Horton, 2002; Glazier, 2010; Cole & Grimshaw, 2014) as well as the magnitude of the X-factor and clubhead velocity (Lephart et al., 2007; Chu et al., 2010). These inconsistent findings may be due to different methods being employed to quantify trunk movement. For example, some studies have used angles determined in the transverse plane (e.g. Chu et al., 2010) whereas other studies have utilised Cardan angles (Joyce et al., 2013; Kwon et al., 2013). The latter method is more anatomically and technically correct when analysing mechanics of the lower back, and this may make the measurement of the crunch factor more anatomically meaningful (Morgan et al., 1997; Cole

& Grimshaw, 2014). Furthermore, when examining lower back movement, the trunk should be modelled with multiple segments (trunk and lower trunk) rather than a single segment due to the varying kinematics of these segments. This may also avoid ambiguous measures of the crunch factor (Joyce et al., 2010; Kwon et al., 2013; Cole & Grimshaw, 2014). The interaction of multiple trunk segments, including proximal to distal segment sequencing has been shown to be important in producing clubhead velocity (Tinmark et al., 2010; Horan & Kavanagh, 2012). Using cross-correlation analyses it has been found that strong 'coupling', or relationships exists between the torso and pelvis segments in the golf swing (Horan et al., 2012). However, the consideration of multiple trunk segments when analysing the crunch factor has not previously been investigated. It is also unknown if a between-segment relationship exists for crunch factor variables, i.e. is axial rotation velocity of the trunk related to that of the lower trunk.

Investigations into the crunch factor have predominantly focused on its association with low back pain (Hosea & Gatt, 1996; Cole & Grimshaw; 2008). However, the effect of crunch factor on swing (clubhead velocity) and launch (launch angle of the ball) parameters have yet to be investigated. It was previously suggested that an increase in lateral bending of the trailing side results in more force being applied into the ball at impact (Gluck et al., 2007). However, despite experimental investigations using projected angles in the transverse plane reporting an association between X-factor, axial rotation velocity and clubhead velocity (Lephart et al., 2007; Chu et al., 2010), none have shown a positive association between increased lateral bending of the trailing side with clubhead velocity (Chu et al., 2010; Joyce et al., 2013). It has also been disputed anecdotally that an increase in lateral bending of the trailing side will facilitate 'hitting-up' on the ball, promoting higher launch angles (Foley, 2012). While it has been reported that although lateral bending of the trunk's trailing side helps to increase the upward path of the clubhead towards impact, excessive trunk lateral bending will restrict trunk rotation velocity and thus, reduce the magnitude of the crunch factor (Chu et al., 2010). However, the effect of crunch factor in isolation on launch angle of the golf ball has not previously been investigated.

The first aim of the study was to investigate the relationship between the trunk and lower trunk for axial rotation velocity and lateral bending (crunch factor variables). The coordination between the trunk and lower trunk segments was also examined. The second aim of the study was to determine the level of association between axial rotation velocity and lateral bending of the trunk and lower trunk with swing (clubhead velocity) and launch (launch angle) parameters. These aims were investigated in a group of high level amateur male golfers using their own driver.

Methods

Participants & Experimental Protocol

Thirty five high level amateur male golfers (Mean ± SD: age = 23.8 ± 2.1 years, registered golfing handicap = 5 ± 1.9) were recruited for this study. Each participant was given a modified Nordic Low Back Pain questionnaire (Kuorinka et al., 1987) to confirm an absence of back pain within the last 12 months. All participants utilised a 'modern' rather than a 'classic' swing (Gluck et al., 2007) and this was confirmed via a qualitative video analysis of each participant's swing. This analysis was performed independently by two Australian Professional Golfers Association teaching professionals. Presence of factors associated with a classic golf swing, i.e. heel raise and pelvic movement, resulted in exclusion from the study. On the basis of these criteria five of the originally screened 40 participants were excluded.

The experimental protocol of this study involved each participant hitting five shots with their own driver using the same leading brand of golf ball. 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 five metres in front of the hitting area. This study was undertaken in an indoor biomechanics laboratory. Ethical approval to conduct the study was provided by the Institutional Human Research Ethics Committee.

Data Collection

A 10-camera MX-F20 Vicon-Peak Motion Analysis System (Oxford Metrics, Oxford, UK) operating at 500 Hz was used to capture 3D coordinates from retro-reflective markers during the golf swing. 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 (Table I). The top of the backswing was defined as the frame where the two club markers changed direction to initiate the downswing (Lephart et al., 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). A validated real-time launch monitor (PureLaunch™, Zelocity, USA) was positioned at a distance of 3m adjacent to the participant’s target line to determine clubhead velocity and launch angle at ball impact (Joyce et al., 2014).

INSERT TABLE I ABOUT HERE

Data Analysis

From the five trials recorded for each driver, the trials with the fastest and slowest clubhead velocity 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 improper contact had been made were analysed. All kinematic trials were smoothed using a Woltring filter with a mean square error of 20mm² (Woltring, 1986).

The multi-segment model used in this study was developed using 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. With previous research (Morgan et al., 1997) and pilot work in this study indicating that the crunch factor is maximised at ball impact, all kinematic variables (and launch monitor variables) were determined at this point. Eight kinematic variables relating to the trunk and lower trunk segments, in addition to two variables collected from the launch monitor (clubhead velocity and launch angle), were analysed in this study (see Table II). Ensemble averages for the crunch factor determined for the trunk and lower trunk from the top of the backswing to ball impact were created. All data were time normalised (0-100%) using cubic spline interpolation.

Cross-correlation analysis was used to investigate the coordination between the trunk and lower trunk segments for the crunch factor variable. Specifically, the lag, or phase difference between the two wave forms was examined (from the data shown in Figure I). A maximum phase difference of 50 samples was examined to ensure at least half the data were overlapping (101 time-normalised downswing data points). As the magnitude of the crunch factor for the trunk and lower trunk differed, a normalised cross-correlation coefficient was obtained (-1 to 1) (Derrick & Thomas, 2004). For R^2 values > 0.8 these were defined as high, 0.7 – 0.8 moderate, and < 0.7 low (Vincent, 2005). As cross-correlation values are not normally distributed, a Fisher *Z*-transformation of the normalised cross-correlation coefficient was performed (Derrick & Thomas, 2004).

Statistical Analysis

All statistical analyses were performed using SPSS V22.0 for Windows (IBM Co., NY, USA). The average of three trials were used for each variable for each participant, with intraclass correlation coefficients [ICC (3,1)] and standard error of mean (SEM) statistics used to determine within-trial reliability of all variables listed in Table II. All data were screened to assess normality, and 95% confidence intervals for crunch factor and launch monitor variables are reported. Bivariate Pearson Product-Moment Correlation analyses were performed to investigate relationships for all kinematic variables between the trunk and lower trunk. 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).

Two generalised linear models (GLM) were used to determine which kinematic variables were associated with clubhead velocity and launch angle. All eight variables were entered into each model then non-significant variables were removed one at a time until only significant variables remained in the final model. The GLM was not used for the first aim, as multicolinearity of the kinematic variables; crunch factor, lateral bending and axial rotation velocity would cause the information matrix to become ill-conditioned and cause difficulty with the reliability of the estimates of the model parameters, e.g. inflated standard errors (Alin, 2010).

Results

Kinematic variables with 95% confidence intervals are described in Table II. Figure I shows the ensemble average of crunch factor for both the trunk and lower trunk segments from top of backswing to ball impact. This figure shows that the crunch factor of the trunk (and shoulder) movement is of a higher magnitude in the latter part of the downswing, than that of the lower trunk. Maximum crunch factor was found to occur 0.032 s (± 0.045 s) and 0.015 s (± 0.070 s) after ball impact for the trunk and lower trunk, respectively. Pearson correlation analysis revealed a moderate and positive relationship for axial rotation velocity ($r(35) = .47$, $p < .01$) between the trunk and lower trunk although, no correlation was reported for lateral bending ($r(35) = .14$, $p > .05$) and thus, crunch factor ($r(35) = .12$, $p > .05$). Cross-correlation analysis of crunch factor between the trunk and lower trunk revealed a high normalised R^2 value of 0.98 (2.27 Fisher *Z*-score). It was also reported that no lag (phase difference) was present for crunch factor between the trunk and lower trunk.

INSERT TABLE II ABOUT HERE

The two GLMs are shown in Table III. The GLM for clubhead velocity reported trunk crunch factor ($p < .01$), lower trunk axial rotation ($p < .01$), lower trunk axial rotation velocity ($p < .05$) and lower trunk crunch factor ($p < .05$) as a significantly associated variables ($p < .05$) with faster clubhead velocity, $b = .00$, $t(35) = 22.23$, $p < .01$, $b = .16$, $t(35) = 6.68$, $p < .01$, $b = -.02$,

$t(35) = 4.61$, $p < .05$, and $b = -.00$, $t(35) = 6.41$, $p < .05$, respectively. The GLM for clubhead velocity can be described by the following equation:

Clubhead velocity (predicted) = intercept + Trunk crunch factor $\bar{x}$ *(0.001) + Lower trunk axial rotation* $\bar{x}$ *(0.163) + Lower trunk axial rotation velocity* $\bar{x}$ *(-0.017) + Lower trunk crunch factor* $\bar{x}$ *(-0.001)*

The model estimates and statistics are depicted in Table III. By interchanging estimates into the equation, predicted clubhead velocity can be determined for any individual, dependent upon the four associated variables. For example, for an individual with a trunk crunch factor of 9486.0 deg^2/s, a lower trunk axial rotation of 13.6º, a lower trunk axial rotation velocity of 123.9 deg/s and a lower trunk crunch factor of 1002.2 deg^2/s, would have a predicted clubhead velocity of 51.9 m/s. The GLM for launch angle resulted in trunk axial rotation ($p < .01$) and lower trunk lateral bending ($p < .05$) as being significantly associated with clubhead velocity, $b = -.19$, $t(35) = 31.39$, $p < .01$ and $b = -.13$, $t(35) = 5.69$, $p < .05$, respectively. The model found that as trunk axial rotation and lower truck lateral bending increased, the launch angle decreased. The final model for launch angle can be described by the following equation:

Launch angle (predicted) = intercept + Trunk axial rotation $\bar{x}$ *(-0.189) + Lower trunk lateral bending* $\bar{x}$ *(-0.130)*

The model estimates and statistics are depicted in Table III. By interchanging estimates into the equation, predicted launch angle can be determined for any individual dependent upon trunk axial rotation and lower trunk lateral bending. For example, for an individual with a trunk axial rotation of 24.9º and a lower trunk lateral bending of 8.5º, would have a predicted launch angle of 8.0º.

INSERT TABLE III ABOUT HERE

Discussion

Dissimilar findings on the relationship between crunch factor and low back pain (Sugaya et al., 1999; Lindsay & Horton, 2002; Glazier, 2010; Cole & Grimshaw, 2014) may possibly be due to the use of ambiguous three dimensional methods. The use of multi-segment trunk models which have been used to further understand segment interaction when producing clubhead velocity (Tinmark et al., 2010; Horan & Kavanagh, 2012; Joyce et al., 2013), may make crunch factor more anatomically meaningful (Morgan et al., 1997; Cole & Grimshaw, 2014).

The first aim of the study was to investigate the relationship for crunch factor between the trunk and lower trunk. Pearson correlation analysis revealed a moderate and positive relationship for axial rotation velocity between the trunk and lower trunk although, no correlation was reported for lateral bending and thus, crunch factor. This agrees with previous experimental research that lateral bending is probably not as important as axial rotation velocity when maximising clubhead speed (Chu et al., 2010; Joyce et al., 2013). This would then suggest that during the downswing, faster axial rotation of the lower trunk transfers to the trunk through the summation of segments seen in the golf swing (Tinmark et al., 2010; Horan & Kavanagh, 2012). Figure I shows the interaction between the trunk and lower trunk for crunch factor during the downswing from the top of the backswing to ball impact.

The use of cross-correlation analysis revealed a high correlation for crunch factor wave forms between the trunk and lower trunk, with no lag or, phase difference being evident. The instance of maximum crunch factor was in agreement with previous research with this variable being maximised just after ball impact for both the trunk and lower trunk segments (Morgan et al., 1997; Sugaya et al., 1999). However, both axial rotation velocity and lateral bending of the trunk at ball impact were larger than that of the lower trunk which suggests the trunk segment is more active during the downswing. This is also supported by the steepness of the ensemble average curve for the trunk (Figure I). This slope links with the cross-correlation findings for segment-coupling reported by Horan & Kavanagh (2012) where, the thorax-pelvis coupling reports a strong R^2 value, and the motion of the thorax during the downswing assists in producing clubhead speed at ball impact.

INSERT FIGURE I ABOUT HERE

The second aim of the study was to investigate the effect of crunch factor variables on swing (clubhead velocity) and launch (launch angle) parameters. Firstly, for clubhead velocity the GLM showed that significant associations with trunk crunch factor ($p < .01$), lower trunk axial rotation ($p < .01$), lower trunk axial rotation velocity ($p < .05$), and lower trunk crunch factor ($p < .05$) were evident. Positive beta coefficients for trunk crunch factor and lower trunk axial rotation indicated that to increase clubhead velocity, these values are increased. Trunk crunch factor had the largest *F*–value of the four variables (22.23), indicating the strongest association with clubhead speed. The methods used in this study therefore suggest that increased crunch factor produces faster clubhead speeds, similar to that of the X-factor (Lephart et al., 2007; Chu et al., 2010). Despite previous research suggesting low back pain is associated with crunch factor (Hosea & Gatt, 1996; Cole & Grimshaw; 2008), no research has investigated crunch factor from a performance perspective. Negative beta coefficients for lower trunk axial rotation velocity and lower trunk crunch factor indicate that to increase clubhead velocity, these values are decreased. It would suggest that lower trunk crunch factor variables (crunch factor itself and axial rotation velocity) are not important in producing faster clubhead velocities. This supports the data and findings related to Figure I, that the trunk segment is more active in the downswing. These findings also support the kinematics which are seen in the modern golf swing, which was previously described as greater shoulder turn, and reduced hip movement at the top of the backswing (Gluck et al., 2007).

For launch angle, the GLM reported significant associations with trunk axial rotation ($p < .01$) and lower trunk lateral bending ($p < .05$). Beta coefficients for both these variables were negative, indicating a reduced axial rotation of the trunk as well as lower trunk lateral bending resulted in an increased launch angle. Negative correlations for trunk axial rotation and driver clubhead velocity have previously been reported at ball impact (Kwon et al., 2013), possibly to return the body and clubhead to a position required for straight driver shots. This is also supported by Hume et al. (2005), who stated in their narrative review that at ball impact, hip rotation is greater than shoulder rotation. This also supports the finding from the GLM for clubhead velocity where lower trunk axial rotation had a positive beta coefficient. With reduced lower trunk lateral bending shown to increase launch angle, this was found both anecdotally, where ‘hitting-up’ on the ball was reported not to produce higher launch angles (however, lateral bending of the trunk was not reported in the GLM) (Foley, 2012), and experimentally, where excessive lateral bending restricts rotation velocity and thus, the magnitude of crunch factor (Chu et al., 2010). Interestingly, lower trunk crunch factor was found to be negatively associated with faster clubhead velocities, and may support the previous finding for the launch angle GLM. With respect to both GLMs, the optimal launch conditions for highly skilled golfers report that faster clubhead velocities are associated with lower launch angles when optimising distance (Wallace et al., 2007; Wishon, 2013). The crunch factor variables reported by each GLM would support body positioning at ball impact to produce these optimal launch conditions.

Previous authors have reported excessive spinal loading and the potential for injury at ball impact where, trunk lateral bending coupled with fast trunk axial rotation velocity are required to produce faster clubhead velocity (Gluck et al., 2007; Sato et al., 2013). It is important to note that the golfers who participated in this study all reported no incidence of low back pain within the last 12 months. Based on the variables selected for both GLMs, this could suggest that the golfers in this study avoid crunch factor related low back injury by minimising the amount of lateral bending at ball impact, so that trunk and lower trunk segment axial rotation and axial rotation velocity are not restricted during the downswing and maximise clubhead velocity (Chu et al., 2010). It has been found that low level amateur golfers (who display high variability in their golf swings) exhibit 80 % greater peak lateral bending of the trunk, leading to increased shear loads on the lower back, than that of professionals (Hosea & Gatt, 1996; Metz, 1999). This could explain why lateral bending was not shown to be important for both aims of this study, based on the cohort used.

A limitation of the study was the use of only kinematic variables related to crunch factor when explaining swing (clubhead velocity) and launch (launch angle) parameters in the GLMs. Despite crunch factor variables showing significant associations for both clubhead velocity and launch angle models, the addition of other kinematic variables (e.g. wrist kinematics) may have given further explanation of the summation of segments in producing each parameter (Chu et al., 2010; Tinmark et al., 2010; Horan & Kavanagh, 2012). Another limitation was that while the 3D methods used were more anatomically meaningful than that of reporting plane-projected angles, the use of acromion markers does not lead to the definition of a solid trunk segment. Finally, it is possible that skin movement artefact may have affected the reported kinematics (Leardini et al., 2009).

In conclusion, the purpose of this study was to firstly investigate the relationship of crunch factor variables between the trunk and lower trunk, then secondly, to see what crunch factor variables are associated with swing (clubhead velocity) and launch (launch angle) parameters. Firstly, a relationship was reported for axial rotation velocity, but no correlation for lateral bending and thus, crunch factor was reported, using a Pearson correlation analysis. Cross-correlation analysis revealed a strong coupling relationship for the crunch factor between the trunk and lower trunk. Secondly, reduced lateral bending at ball impact was shown to be related to faster driver clubhead velocities and a lower launch angle. These findings have implications for both injury prevention and improved golf performance.

References

Alin, A. (2010). Multicolinearity. *Interdisciplinary Reviews: Computational Statistics, 2*(3), 370-374.

Cheetham, P., Martin, P., & Mottram, R. (2001). The importance of stretching the "X-factor" in the downswing of golf: The "X-factor stretch". In: Thomas, P. R. (4th Ed). *Optimising Performance in Golf*. (pp.192-199). Brisbane, QLD: Australian Academic Press Ltd.

Cole, M.H., & Grimshaw, P.N. (2008).Trunk muscle onset and cessation in golfers with and without low back pain. *Journal of Biomechanics, 41*(13), 2829-2833.

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.

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.

Derrick, T. R., & Thomas, J. M. (2004). Time series analysis: The cross-correlation function. In N. Stergion (Ed.), Innovative analyses of human movement (pp. 189–205). Champaign, IL: Human Kinetics.

Foley, S. (2012, February). Hit down with your driver. *Golfers Digest*. Retrieved November 6, 2014, from http://www.golfdigest.com/golf-instruction/2012-02/sean-foley-down-driver

Glazier, P. (2010). Is the 'crunch factor' an important consideration in the aetiology of lumbar spine pathology in cricket fast bowlers? *Sports Medicine, 40*(10), 809-815.

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

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.

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

Hume, P., Keogh, J., & Reid, D. (2005). The role of biomechanics in maximising distance and accuracy of golf shots. *Sports Medicine, 35* (5), 429–449.

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

Joyce, C., Burnett, A., & 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.

Joyce, C., Burnett, A., Ball, K., & Cochrane, J. (2013). 3D trunk kinematics in golf: between-club differences and relationships to clubhead speed. *Sports Biomechanics, 12*(2), 108-120.

Joyce, C., Burnett, A., Reyes, A., & Herbert, S. (2014). A dynamic evaluation of how kick point location influences swing parameters and related launch conditions. *Proceedings of the Institution of Mechanical Engineers Part P: Journal of Sports Engineering and Technology, 228*(2), 111-119.

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.

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.

Leardini, A., Biagi, F., Belvedere, C., & Benedetti, M.G. (2009). Quantitative comparison of current models for trunk motion in human movement analysis. *Clinical Biomechanics, 24*, 542-550.

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.

Lindsay, D.M., & Horton, J.F. (2002).Comparison of spine motion in elite golfers with and without low back pain. *Journal of Sports Sciences, 20*(8), 599-605.

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.

McLean, J. (1992). Widening the gap. *Golf Magazine, 12*, pp. 49-53.

Metz, J.P (1999). Managing golf injuries. *The Physician and Sports medicine, 39*, 62-74.

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.

Sato, K., Kenny, I.C., & Dale, B.R (2013).Current golf performance literature and application to training. *Journal of Trainology, 2*(2), 23-32.

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.
Vincent, W. J. (2005). Statistics in kinesiology (3rd Ed.). Champaign, IL: Human Kinetics.

Wallace, E.S., Otto, S.R., & Nevill, A. (2007). Ball launch conditions for skilled golfers using drivers of different lengths in an indoor testing facility. *Journal of Sports Sciences, 25*, 731-737.

Wishon, T. (2013, August).A complete guide to fitting for maximizing distance. *Wishon Golf*. Retrieved December 24, 2014, from http://wishongolf.com/etech/archive/2013-2/august-2013/

Woltring, H.J. (1986). A FORTRAN package for generalised, cross-validatory spline smoothing and differentiation. *Advanced Engineering Software, 8*(2), 104-113.

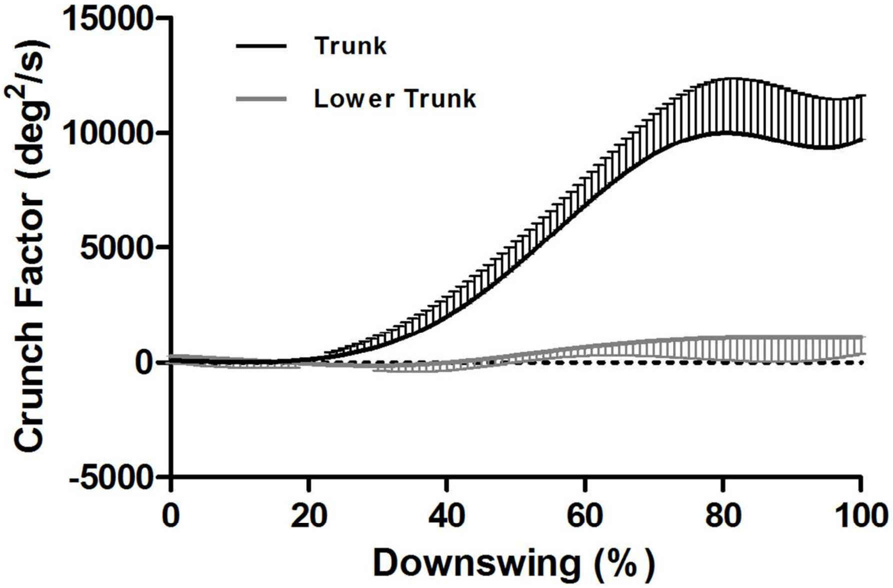
Tables & Figure

Table I Anatomical placement of the retro-reflective markers.

Table II Crunch factor variables reported for the trunk and lower trunk segments and swing and launch parameters (Mean ± SD). The 95% confidence intervals are reported, along with indices of reliability.

Table III Final generalised linear model estimates for clubhead velocity and launch angle.

Figure I Ensemble averages of crunch factor data reported for the trunk and lower trunk segments from the top of the backswing (0 %) to ball impact (100 %). Shaded areas represent one standard deviation from the mean.



Ensemble averages of crunch factor data reported for the trunk and lower trunk segments from the top of the backswing (0 %) to ball impact (100 %). Shaded areas represent one standard deviation from the mean.
110x73mm (300 x 300 DPI)

Table 2

Reference Frame	Anatomical Marker Placement	Defined Joint Coordinate System
Shoulders[1]	Left Acromion Process (LACRM) Right Acromion Process (RACRM) Tenth Thoracic Spinous Process (T10)	Mid-acromion, then T10 mid-point (origin). Mid-acromion, unit vector pointing right (X vector). A distal unit vector perpendicular to X from the origin (Y-temp vector). Common perpendicular of X and Y-temp, proximal unit vector, perpendicular to X (Z vector). Cross-product of X and Z, a unit vector perpendicular and anterior to X.
Lower Thorax[2]	Xiphoid Process, distal end of the Sternum Tenth Thoracic Spinous Process (T10) First Lumbar Spinous Process (L1)	Mid-L1 and T10, then mid-sternum (origin). Mid-L1 and T10, unit vector pointing right (X vector). A distal unit vector perpendicular to X from the origin (Y-temp vector). Common perpendicular of X and Y-temp, proximal unit vector, perpendicular to X (Z vector). Cross-product of X and Z, a unit vector perpendicular and anterior to X.
Pelvis[2]	Left Anterior Superior Illiac Spine (LASIS) Right Anterior Superior Illiac Spine (RASIS) Left Posterior Superior Illiac Spine (LPSIS) Right Posterior Superior Illiac Spine (RPSIS)	Mid-point of mid-ASIS and mid-PSIS (origin). Unit vector pointing right from the origin (X vector). A distal unit vector perpendicular to X from the origin (Y-temp vector). Common perpendicular of X and Y-temp, proximal unit vector, perpendicular to X (Z vector). Cross-product of X and Z, a unit vector perpendicular and anterior to X.
Golf Club	1/3 length of shaft from grip 2/3 length of shaft from grip	None

[1] – Trunk, [2] – Lower Trunk. Joint coordinate systems defined from anatomical position perspective.

Table II Crunch factor variables reported for the trunk and lower trunk segments and swing and launch parameters (Mean ± SD). The 95 % confidence intervals are reported, along with indices of reliability.

Variable	Segment	Mean (± SD)	95% Lower – Upper CI	ICC	SEM
Crunch factor (deg^2/s)	Trunk	9486.0 (± 1945.6)	9109.5 – 9862.6	0.978	288.6
	Lower trunk	1002.2 (± 618.8)	882.5 – 1122.0	0.970	107.2
Lateral bending (deg)	Trunk	30.6 (± 4.9)	29.6 – 31.5	0.991	0.5
	Lower trunk	8.5 (± 4.7)	7.6 – 9.5	0.970	0.8
Axial rotation (deg)	Trunk	24.9 (± 7.6)	23.5 – 26.4	0.979	1.1
	Lower trunk	13.6 (± 4.1)	12.8 – 14.4	0.965	0.8
Axial rotation velocity (deg/s)	Trunk	317.4 (± 38.2)	310.0 – 324.7	0.885	13.0
	Lower trunk	123.9 (± 34.7)	117.2 – 130.6	0.910	10.4
Clubhead velocity (m/s)		48.1 (± 3.0)	47.5 – 48.7	0.969	0.5
Launch angle (deg)		8.0 (± 2.7)	7.4 – 8.5	0.825	1.1

CI – Confidence intervals, ICC – intra-class correlation coefficient, SEM – standard error of measurement

Table III Final generalised linear model estimates for clubhead velocity and launch angle.

Model	Variables	β – coefficient	Standard error	p – value
	Intercept	*43.254*	*1.927*	*0.000*
Clubhead velocity	Trunk crunch factor	0.001	0.000	0.000
	Lower trunk axial rotation	0.163	0.063	0.010
	Lower trunk axial rotation velocity	-0.017	0.008	0.032
	Lower trunk crunch factor	-0.001	0.000	0.011
	Intercept	*13.791*	*1.146*	*0.000*
Launch angle	Trunk axial rotation	-0.189	0.034	0.000
	Lower trunk lateral bending	-0.130	0.054	0.017