Journal of Sports Sciences
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713721847

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First published on: 14 September 2010

To cite this Article Chu, Yungchien , Sell, Timothy C. and Lephart, Scott M.(2010) 'The relationship between biomechanical variables and driving performance during the golf swing', Journal of Sports Sciences, 28: 11, 1251 — 1259, First published on: 14 September 2010 (iFirst)

To link to this Article: DOI: 10.1080/02640414.2010.507249

URL: http://dx.doi.org/10.1080/02640414.2010.507249

Journal of Sports Sciences, September 2010; 28(11): 1251–1259

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The relationship between biomechanical variables and driving performance during the golf swing

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(Accepted 6 July 2010)

Abstract

Swing kinematic and ground reaction force data from 308 golfers were analysed to identify the variables important to driving ball velocity. Regression models were applied at four selected events in the swing. The models accounted for 44–74% of variance in ball velocity. Based on the regression analyses, upper torso–pelvis separation (the X-Factor), delayed release (i.e. the initiation of movement) of the arms and wrists, trunk forward and lateral tilting, and weight-shifting during the swing were significantly related to ball velocity. Our results also verify several general coaching ideas that were considered important to increased ball velocity. The results of this study may serve as both skill and strength training guidelines for golfers.

Keywords: *Golf swing, biomechanics, driving performance*

Introduction

Better driving performance is a primary focus of most golfers. Through years of experience and qualitative research, golf teaching professionals have anecdotally described the swing mechanics as the most important for optimal golf driving performance (Adlington, 1996). Golf professionals aim to educate a golfer on the best approach to manoeuvre the body and club during the swing, which will transfer the most amount of energy into the ball and maximize the driving distance (Adlington, 1996; Farrally et al., 2003; Hume, Keogh, & Reid, 2005). For example, Adlington (1996) stated that the golfer must have a straight back, bent slightly forward at the address position and perpendicular to the ground throughout the swing; the body weight should shift towards the trailing foot (i.e. the right foot for a right-handed golfer) during the backswing and then back towards the leading foot (i.e. the left foot for a right-handed golfer) at the completion of the follow-through position; and the movement of body segments should be sequential from the ground up.

Different research approaches have been used to validate the professionals' belief and investigate the key elements of driving performance. Mathematical models have been devised to describe aspects of the golf swing from a physics perspective (Milburn, 1982; Miura, 2001; Penner, 2003). Variables such as wrist hinge angle, club release angle, and torques applied by shoulders and wrists throughout a swing were estimated by adjusting a double pendulum model to match a real golf swing (Jorgensen, 1994). These models were further refined in search of skills that can be applied by golfers to improve club head velocity, proportional to driving distance (Shamus & Shamus, 2001) and inversely proportional to lower handicap (a lower handicap indicates better playing ability for an amateur golfer) (Fradkin, Sherman, & Finch, 2004). An increased backswing angle (Reyes & Mittendorf, 1998), delayed release (i.e. the initiation of movement) of the club (Pickering & Vickers, 1999), increased torque applied at the hub of arms (i.e. the mid-point of the shoulders) and club rotation (Jorgensen, 1994), and lateral (Jorgensen, 1994) and upward shift (Miura, 2001) of the hub have all been associated with an increase in club head velocity.

The *in vivo* measurement and calculation of the kinematics, kinetics, and neuromuscular characteristics of golfers is another approach to determining the characteristics that separate good golfers from the

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ISSN 0264-0414 print/ISSN 1466-447X online © 2010 Taylor & Francis
DOI: 10.1080/02640414.2010.507249

rest. Cooper and Mather (1994) found that professional golfers maximized their club head angular velocity exactly at ball impact, low-handicap golfers peaked just prior to impact, while high-handicap golfers peaked in early downswing. The findings of Robinson (1994) indicated that less skilled golfers released and accelerated their club too early. Sequential trunk rotation was found in professional golfers (McTeigue, Lamb, & Mottram, 1994), and the trunk rotation was quicker in professionals than amateurs (McTeigue et al., 1994; Robinson, 1994). The separation between the pelvis and upper torso orientation (often referred as the X-Factor in golf) is a sign of sequential trunk rotation. It was found to be higher (i.e. increased separation between the pelvis and upper torso orientation) in professionals (Cheetham, Martin, & Mottram, 2000), low-handicap golfers (Watanabe, Kuroki, Hokari, & Nishizawa, 1998), golfers with high ball velocity (Myers et al., 2008), and professionals with high driving distance (McLean, 1992). Low-handicap golfers adopt more (Kawashima, Meshizuka, & Takeshita, 1999; Koenig, Tamres, & Mann, 1994; Wallace, Graham, & Bleakley, 1990) and quicker (Okuda, Armstrong, Tsunezumi, & Yoshiike, 2002; Wallace et al., 1990) weight shift of the body back towards the trailing foot in the backswing and then shift forward towards the leading foot in the downswing.

Despite this extensive collection of research, previous studies that comprehensively evaluated the relative importance of biomechanical variables and their role in maximizing the driving performance have been limited. The current study, instead of verifying the importance of several biomechanical features, evaluated multiple variables throughout the golf swing to determine the key factors among them. By elucidating the biomechanical factors most important to driving performance, training programmes can be constructed to enhance those physical characteristics that may improve upon the key biomechanical components of the golf swing. Therefore, the purpose of this study was to identify and validate the most important factors contributing to driving performance in a diverse group of golfers.

Methods

Participants

Three hundred and eight golfers (266 males, 42 females) participated in this study (mean ± *s*: age 43.2 ± 15.6 years, height 1.77 ± 0.17 m, mass 83.5 ± 17.0 kg, USGA handicap 8.4 ± 8.4). All participants were free of injury and had no significant history of joint injury at the time of testing. All participants signed an informed consent as required by the university's institutional review board.

Instrumentation

Kinematic data of the golf swing were collected with eight high-speed cameras working at 240 Hz controlled by the Peak Motus System (Peak Performance Technologies, Inc., Englewood, CO). The accuracy of this motion capture system was reported as 4.68 mm and 0.56° (Ehara, 2002). Two Kistler force platforms (one under each foot) (Kistler Instrumente AG, Winterthur, Switzerland) operating at 1200 Hz were synchronized with the cameras by the Peak Motus System to collect ground reaction force data. We used ball velocity as the driving performance variable, which was assessed with the FlightScope® Sim Sensor (EDH Ltd., Stellenbosch, South Africa) integrated with AboutGolf® (AboutGolf Ltd., Maumee, OH) simulation software. The Sim Sensor applies three-dimensional phase-array microwave technology that operates at 7 kHz to track ball flight from club impact until impact with a screen 5 m away.

Procedures

Anthropometric measurements of the lower extremity were taken including body mass and height, anterior-superior iliac spine breadth, thigh, calf and foot length, mid-thigh and calf circumference, knee diameter, malleolus height, malleolus width, and foot breadth. Anthropometric measurements of the upper extremity included upper arm length, forearm length, forearm diameter, hand length, hand diameter, and hand width. Participants were fitted with reflective markers (0.025 m diameter) at the following lower extremity landmarks bilaterally: the posterior heel, lateral malleolus, second metatarsal head, femoral epicondyle, anterior-superior iliac spine, and sacrum. Reflective markers were placed at the following upper extremity landmarks bilaterally: acromion, lateral epicondyle of the humerus, wrist, and T4 level of the spine. Eight markers were attached to wands (distance of 0.09 m from the skin) and secured with Velcro straps on the lateral side of bilateral mid-thigh, mid-calf, mid-forearm, and mid-upper arm (Figure 1). Two markers were placed on each side of the body at the L5/S1 level to locate the centre of the lumbo-sacral joint. Two markers were placed on the golf club to identify the phases of the golf swing. The trajectories of markers were tracked by the high-speed cameras and filtered using an optimized cut-off frequency (Jackson, 1979).

Each participant was instructed to perform his or her typical warm-up before data collection. Data collection consisted of each participant standing on the two force platforms to hit 10 shots off an artificial turf tee box into a projected practice range image on the screen controlled by AboutGolf® software.

Figure 1. Reflective marker placements.

Data reduction

Of the ten shots, the five with the highest ball velocity were analysed and averaged. Selected kinematic variables and ground reaction forces (Table I, Figure 2) were calculated at four critical events of the golf swing: top of the swing, acceleration (two-thirds of the time elapsed from top of swing to impact), 40 ms prior to impact, and impact. The selected events and the time elapsed relative to the full duration of the downswing are presented in Figure 3. Top of the swing and impact were events used in several studies (Ball & Best, 2007; Robinson, 1994; Wallace et al., 1990). Based on communication with golf teaching and touring professionals, key kinematic activities occur between top of the swing and impact. Therefore, additional events between top of the swing and impact should be established and can be used as checkpoints for kinematic adjustment. The selection of acceleration and 40 ms prior to impact was based on the fact that they are identifiable in every golfer, and they are considered relevant based on the professional opinions we obtained. In previous studies, ground reaction forces were presented in the form of percentage distribution (Fz%) between the two feet (Ball & Best, 2007; Robinson, 1994). We chose to use the measured forces directly as we believed that not only the distribution but the amount of force a golfer exerts against the ground is a key factor of the swing.

Table I. Selected kinematic and ground reaction force variables.

Leading hip flexion (positive for flexion, 0° for neutral position)
Leading knee flexion (positive for flexion, 0° for neutral position)
Upper torso rotation and rotational velocity (positive for rotating forward, 0° for neutral position)
Pelvis rotation and rotational velocity (positive for rotating forward, 0° for neutral position)
X-Factor and changing rate (positive when upper torso leads pelvis, 0° for neutral position)
Trunk lateral bend and bending velocity (positive for bending towards the trailing side, 0° for neutral position)
Trunk forward tilt (positive for forward tilt, 0° for neutral position)
Wrist hinge angle and rotational velocity (positive for curled wrist, 0° for neutral)
Pelvis medial-lateral shift and velocity (positive for shifting forward)
Pelvis superior-inferior shift and velocity (positive for shifting upward)
Leading arm angle (0° for the leading arm points forward)
Leading/trailing vertical ground reaction force and changing rate

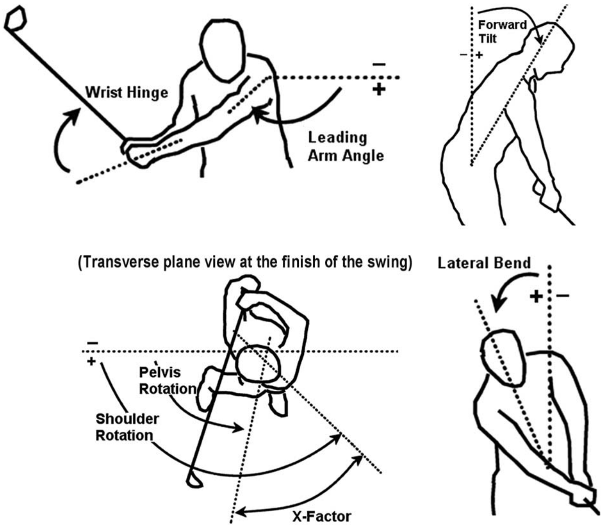

Figure 2. Selected kinematic variables.

Statistical analysis

A stepwise linear multiple regression was used to determine the significant predictors of ball velocity at each critical event. Stepwise regression is a statistical method to determine whether certain independent variables are linearly related to a dependent variable. It adds independent variables into a linear model sequentially based on the variables' significance. With every variable added into the model, all variables already in the model are reviewed and may be removed if no longer significant. Ball velocity was the dependent variable, and the variables listed in Table I were the independent variables. The entry significance level was $P \leq 0.05$, while the removal significance level was $P \geq 0.10$. Standardized beta coefficients were calculated by adjusting each

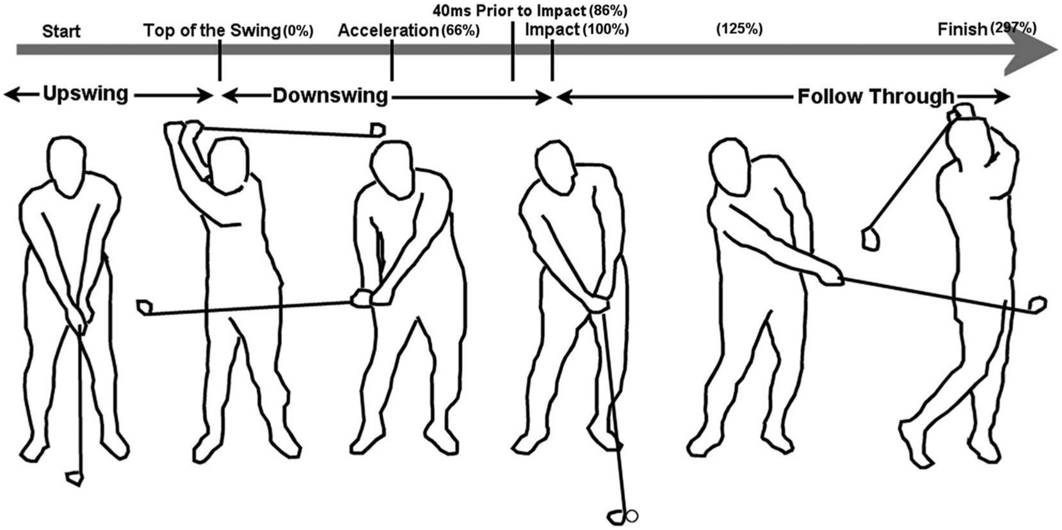

Figure 3. Selected events for analysis.

independent variable to have variances of 1 before applying the linear regressions. The beta coefficient represents the change of dependent variable in unit of standard deviation when an independent variable is changed for one standard deviation. These statistical analyses were performed with SPSS version 15.0 (SPSS Inc., Chicago, IL).

An omnibus, *a priori* power analysis for linear multiple regression models was conducted using G*Power software (University of Kiel, Germany) before fitting the regression models. With $\alpha = 0.05$ and moderate effect size $f2 = 0.15$, 163 participants were needed to achieve the acceptable power of 0.80. With 308 participants recruited in this study, the statistical power was expected to be more than acceptable.

Results

Group means and standard deviations of all variables investigated in this study are listed in Table II. The results of regression analyses, including predictors of ball velocity at each event, the R^2 (coefficient of determination) of each regression model, and the standardized beta coefficients of each predictor are presented in Table III. The ball velocity measured ($61.0 \pm 8.7\ \text{m} \cdot \text{s}^{-1}$, or 136.5 ± 19.4 mph) correlated negatively with handicaps ($r = 0.71$).

Discussion

The purpose of this study was to identify and validate the key factors that contribute to driving ball velocity in a diverse group of golfers. Stepwise linear regressions were performed with the kinematic and ground reaction force variables of 308 golfers at four critical events during the golf swing. The four regression models accounted for 43.7–73.5% of the variance in ball velocity.

The top of the swing is an important event as it ends all preparation for the rapid downswing. An appropriate body position at this instant should be advantageous for the upcoming downswing, and therefore greater ball velocity. Our regression model at this instant accounted for 43.7% of the variance in ball velocity. Based on the standardized beta coefficients, the trunk lateral bending, pelvis superior shift velocity, and the X-Factor were the most important variables at this instant. All predictors included in this model supported the idea of a strong backswing from bottom up. The beta coefficient indicated that with every one standard deviation increase in leading knee flexion angle, ball velocity increased 0.203 standard deviations. The favourable greater leading knee flexion might facilitate the pelvis backward rotation and the backward shift of body weight (Egret, Nicholle, Dujardin, Weber, & Chollet, 2006). Further backward rotation of the trunk, creating a separation between the upper torso and pelvis (the X-Factor, negative values by definition at this instant), was also preferred. Pelvis superior shift velocity and leading arm angle were included in the model, suggesting that greater upward and backward rotation of the arms was favoured. Finally, a greater wrist hinge angle also delivered a positive effect to ball velocity. However, with the strong backswing, coaches also suggest keeping the upper body "perpendicular with the ground (in the frontal plane)" (Adlington, 1996) to prevent a negative trunk lateral bending (towards the leading side), which might affect the efficiency of the following downswing. Most of our golfers followed this guideline, performing a slightly positive lateral bending ($3.9 \pm 7.4^\circ$), which our model also preferred.

Table II. Group means and standard deviations of all selected variables.

	Top	Acceleration	Last 40 ms	Impact
Trunk				
Forward tilt (°)	22.0 ± 7.2	24.2 ± 7.7	23.2 ± 7.9	22.6 ± 7.7
Lateral bend (°)	3.9 ± 7.4	8.6 ± 6.0	11.7 ± 6.0	14.4 ± 6.5
Lateral bend velocity (deg · s^{-1})	7.5 ± 17.9	41.8 ± 50.5	64.6 ± 54.3	66.3 ± 54.0
Medial-lateral shift (m)	−0.02 ± 0.02	−0.02 ± 0.02	0.00 ± 0.03	0.02 ± 0.03
Medial-lateral shift velocity (m · s^{-1})	−0.04 ± 0.08	0.23 ± 0.19	0.36 ± 0.21	0.29 ± 0.21
Superior-inferior shift (m)	−0.03 ± 0.05	0.05 ± 0.05	0.07 ± 0.05	0.09 ± 0.06
Superior-inferior shift velocity (m · s^{-1})	0.27 ± 0.15	0.44 ± 0.26	0.33 ± 0.27	0.27 ± 0.24
X-Factor (°)	−49.0 ± 11.6	−37.3 ± 10.4	−22.5 ± 9.6	−12.3 ± 9.1
X-Factor changing rate (deg · s^{-1})	−41.0 ± 37.9	220.1 ± 87.8	249.6 ± 78.0	271.4 ± 85.3
Upper torso rotation (°)	−98.0 ± 14.1	−37.7 ± 12.7	0.5 ± 9.4	22.9 ± 9.7
Upper torso rotation velocity (deg · s^{-1})	40.6 ± 60.1	608.1 ± 117.5	586.9 ± 99.6	537.0 ± 108.3
Pelvis rotation (°)	−49.0 ± 12.0	−0.4 ± 12.7	23.1 ± 11.5	35.2 ± 12.3
Pelvis rotation velocity (deg · s^{-1})	81.7 ± 62.5	388.1 ± 77.4	337.3 ± 75.2	265.6 ± 79.8
Arms				
Leading arm angle (°)	222.7 ± 9.5	176.3 ± 14.7	133.7 ± 8.5	63.3 ± 6.8
Wrist hinge (°)	81.7 ± 16.1	65.3 ± 13.1	35.3 ± 12.3	13.9 ± 6.8
Wrist hinge rotational velocity (deg · s^{-1})	12.5 ± 52.9	−292.0 ± 154.2	−712.8 ± 208.9	−37.5 ± 415.0
Legs				
Leading hip flexion (°)	21.4 ± 12.8	33.5 ± 8.8	23.9 ± 8.9	16.4 ± 9.1
Leading knee flexion (°)	41.6 ± 11.5	32.9 ± 9.9	22.0 ± 9.8	16.2 ± 9.4
Ground reaction forces				
Leading foot VGRF (%BW)	29.0 ± 12.1	93.9 ± 28.5	95.1 ± 30.5	74.7 ± 29.7
Leading foot VGRF changing rate (%BW · s^{-1})	85.3 ± 169.3	329.6 ± 517.0	−447.9 ± 516.7	−467.5 ± 511.4
Trailing foot VGRF (%BW)	64.5 ± 14.3	46.4 ± 17.3	41.0 ± 21.2	35.5 ± 21.0
Trailing foot VGRF changing rate (%BW · s^{-1})	−112.5 ± 163.1	4.7 ± 290.3	−162.0 ± 314.5	−84.6 ± 292.3

Note: VGRF = vertical ground reaction force, BW = body weight.

It should be emphasized that neither upper torso nor pelvis rotation but rather the X-Factor was considered significant, suggesting that instead of only focusing on increasing the backward rotation of the upper torso and pelvis, golfers should focus on creating the separation between them. McHardy and colleagues (McHardy, Pollard, & Luo, 2006) noted that since the 1960s, a "modern" golf swing focusing on the X-Factor started to replace the "classic" swing that focused on both the upper torso and pelvis rotations, as the modern swing generates greater power for longer shot. Based on the swing kinematics of 100 golfers, Myers et al. (2008) found that the X-Factor, instead of the upper torso or pelvis rotation, was significantly and strongly correlated with ball velocity, and the comparisons across three different velocity groups demonstrated that a greater X-Factor was achieved by the simultaneous increase in upper torso rotation and decrease in pelvis rotation. Limited pelvis backward rotation was previously observed in golfers with greater ball velocity (Bechler, Jobe, Pink, Perry, & Ruwe, 1995; Burden, Grimshaw, & Wallace, 1998; Gatt, Pavol, Parker, & Grabiner, 1998; Okuda et al., 2002). It might be a sign that these golfers started to rotate their pelvis forward even before the top of the swing. Such movement might create a greater X-Factor and facilitate the sequential movement of the trunk (McTeigue et al., 1994). Zheng and colleagues (Zheng, Barrentine, Fleisig, & Andrews, 2008) also found significant differences for the X-Factor between professional and high-handicapped groups, although Cheetham et al. (2000) did not find a significant difference in X-Factors between professional and amateur golfers.

From the top of the swing, the golfer rapidly uncoils and rotates forward, bringing the club head to the ball in 0.30 ± 0.06 s. As the time from acceleration to impact was only 0.10 ± 0.02 s, it is not surprising that many predictors were included in all of the models defined across this short period of time. These three models accounted for 50.5–73.5% of variation in ball velocity. With the initiation of downswing, the body weight, shifted to the trailing foot at the top of the swing, started to shift forward to the leading foot. Greater vertical ground reaction force of the leading foot at acceleration and 40 ms prior to impact, indicating greater weight shifting forward, was preferred as in previous research (Kawashima et al., 1999; Koenig et al., 1994; Wallace et al., 1990). Miura (2001) suggested an upward pull of the swing path when approaching impact can further increase club head velocity. The model at impact indicated that a rapid decrease in

Table III. Significant variables and their beta coefficients selected in regression analyses.

	Model 1 Top	Model 2 Acceleration	Model 3 Last 40 ms	Model 4 Impact
Trunk				
Forward tilt (°)		24.2 ± 7.7 0.144^{d}	23.2 ± 7.9 0.152	22.6 ± 7.7 0.260
Lateral bend (°)	3.9 ± 7.4 0.267	8.6 ± 6.0 0.170^{d}	11.7 ± 6.0 0.162	14.4 ± 6.5 0.278
Lateral bend velocity (deg · s^{-1})		41.8 ± 50.5 0.203	64.6 ± 54.3 0.137^{d}	66.3 ± 54.0 0.148^{c}
Superior-inferior shift (m)				0.09 ± 0.06 0.158^{d}
Superior-inferior shift velocity (m/s)	0.27 ± 0.15 0.300			
X-Factor	−49.0 ± 11.6 −0.252			
Upper torso rotation (°)			0.5 ± 9.4 −0.177	
Upper torso rotation velocity (deg · s^{-1})		608.1 ± 117.5 0.429	586.9 ± 99.6 0.226	537.0 ± 108.3 0.128^{c}
Arms				
Leading arm angle (°)	222.7 ± 9.5 0.203	176.3 ± 14.7 0.118^{b}	133.7 ± 8.5 0.167^{a}	63.3 ± 6.8 -0.227^{d}
Wrist hinge (°)	81.7 ± 16.1 0.133^{c}	65.3 ± 13.1 0.203	35.3 ± 13.0 0.349	13.9 ± 6.8 -0.137^{b}
Wrist hinge velocity (deg · s^{-1})			−712.8 ± 208.9 −0.322	−37.5 ± 415.0 -0.138^{c}
Legs				
Leading knee flexion (°)	41.6 ± 11.5 0.203			
Ground reaction forces				
Leading foot VGRF (%BW)		93.9 ± 28.5 0.194	95.1 ± 30.5 0.215	
Leading foot VGRF changing rate (%BW · s^{-1})				−84.6 ± 292.3 -0.154^{d}
Trailing foot VGRF changing rate (%BW · s^{-1})			−162.0 ± 314.5 0.093	
R^2 of regression equation	0.437	0.660	0.735	0.505

Note: VGRF = vertical ground reaction force, BW = body weight. R^2 = coefficient of determination; beta coefficient = the change of dependent variable in unit of standard deviation when an independent variable is changed for one standard deviation.
$^{a}P < 0.05$, $^{b}P < 0.03$, $^{c}P < 0.02$, $^{d}P < 0.01$ for all other entries, else $P < 0.001$.

vertical ground reaction force of the leading foot and a superior shift of the pelvis were encouraged. Ball and Best (2007) identified a "reverse group" of golfers, shifting their weight back towards the trailing foot after mid-downswing. This is not the case for the decreasing vertical ground reaction force of the leading foot observed here. Presented in the format of force distribution between the two feet (Fz%), our golfers kept the vertical ground reaction force of the leading foot at a consistent level between 66 and 69% towards impact in spite of the decreasing magnitude (like the "front foot group" in Ball & Best, 2007). The decreasing vertical ground reaction force was the result of an upward bodily movement. Therefore, the uppercut swing for higher ball velocity should be achieved by the upward movement of the whole body, instead of only relying on the arms or wrists to pull up the swing path.

As the lower body led the downswing, the upper body lagged, creating a greater lateral bending of the trunk from the global vertical axis towards the trailing side. This bending, selected across these three models, kept increasing towards impact (8.6 ± 6.0°, 11.7 ± 6.0°, and 14.4 ± 6.5°, respectively). As mentioned, an upward swing path approaching impact positively influences club head velocity (Miura, 2001). The lateral bending of the upper body helps to create the upward angle of the club head path towards impact, with the proper alignment among the club, the arms, and the upper body maintained. While this angle was selected starting at the top of the swing, its velocity was determined to be important only in the models from acceleration to impact. This implied that the greater increase of the lateral bending angle should mainly occur in a rather short period of time approaching the impact, as early bending might restrict trunk rotation.

Trunk forward tilt was another predictor from acceleration to follow-through. To utilize trunk rotation to hit the ball on the ground, a golfer must bend his or her trunk forward. Our participants demonstrated very limited changes of this angle across the four events (21.9 ± 7.2°, 24.2 ± 7.7°, 23.2 ± 7.9°, and 22.6 ± 7.7°, respectively), indicating that while it was not yet a predictor at the top of swing, this forward tilt angle should be kept nearly constant from there towards the follow-through, so the trunk rotation could be maintained on a plane. In fact, this angle has been recommended as a "key element of posture" by coaches and should be established as early as the set-up of the swing (Adlington, 1996). The standardized beta coefficient of trunk forward tilt kept increasing from the event of acceleration, and made this variable one of the most important predictor variables at impact. This finding highlighted the efficacy of a long-held belief among golf coaches of the need to maintain the forward tilt angle throughout the swing. We have demonstrated that an overall upward movement of the whole body is encouraged. However, the upward movement, pelvis rotation, and the inclining path of club swing can extend or hyperextend a golfer's upper torso. It could be difficult to perform such upward movement while still maintaining the trunk forward tilt angle. A golfer's core muscles must be strong enough to generate sufficient upper torso flexion torque resisting the extension.

Upper torso rotation velocity as a significant predictor at events following acceleration re-emphasized the importance of trunk rotation, and was the most important predictor at acceleration. The decreasing trend in beta coefficients supported the kinetic chain theory that the peak upper torso rotation velocity should occur before impact so that the energy it possesses can be transferred towards the club in time for impact. Such a decreasing trend of beta coefficients suggested that the relative importance of this variable over other selected variables decreased from acceleration towards impact. *Post-hoc* univariate regressions found that this variable at acceleration explained the variance in ball velocity better than at other events.

Previous simulations reported that delayed release of the club can increase the club head velocity (Pickering & Vickers, 1999; Sprigings & Mackenzie, 2002). The current results further confirmed that the release of the leading arm should also be delayed. The leading arm angle was positively related to ball velocity at both acceleration and 40 ms prior to impact. But the negative relation between the leading arm angle and ball velocity at impact suggested a rapid lead arm movement within the 40 ms before impact. The fact that the wrist hinge angle was also included in these three models supported the idea of delayed but quick wrist release towards impact (Pickering & Vickers, 1999; Sprigings & Mackenzie, 2002). This finding also supports previous research that demonstrated that professional golfers had a greater wrist hinge angle near the event of acceleration (Robinson, 1994). High wrist hinge velocity (negative values by definition when wrist uncurls) was included in the models only after the last 40 ms, implying that early maximal velocity might not help ball velocity. This result supported the simulation of Sprigings and Neal (2000) that an accelerating wrist torque applied between the acceleration and the last 40 ms events in the current study can further increase the club head velocity.

Besides the preferred kinematics described, which would help golf coaching, the results of the current study could also be applied to the development of physical training programmes for golfers. A physical training programme to improve the X-Factor at the top of swing was developed and validated (Lephart, Smoliga, Myers, Sell, & Tsai, 2007). The current results provide biomechanical support to such training programmes. The rapid weight forward shift requires highly activated leading hip adductors (Bechler et al., 1995), which also facilitates the forward rotation of the trunk with the trailing hip external rotators, abductors, extensors (Bechler et al., 1995), and the trunk extensors (Pink, Perry, & Jobe, 1993). Training for the hip flexors and extensors (Bechler et al., 1995), abdominal muscles, and trunk extensors (Pink et al., 1993) is necessary as these muscles are critical for the trunk forward tilt and lateral bend. The wrist hinge has been described an important factor for club velocity (Pickering & Vickers, 1999; Sprigings & Mackenzie, 2002). However, most previously developed training programmes emphasized that the large muscles groups, and the forearm muscles have been essentially overlooked. The current results suggested the forearm muscles could be important to golf performance, as they must provide sufficient torque at the wrists to resist and delay the club release, and provide great angular accelerations after the club release.

There were several limitations to the current study. First, while the performance goal golfers pursue is the driving distance, in our indoor laboratory setting it can only be estimated with ball velocity. Ball velocity might be affected by the club head velocity, launch angle, and ball spin rate (Penner, 2003). Club head velocity was strongly correlated ($r = 0.94$) with the ball velocity in our data, and has also been correlated with greater driving distance (Shamus & Shamus, 2001) and a better handicap index (Fradkin et al., 2004). Launch angle varied within a relatively small range among all participants ($s < 3°$). Ball spin rate in flight may affect the aerodynamic and therefore the driving distance. However, instead of monitoring the spin rate in flight, our equipment can only measure the spin rate in a very short moment after impact. Plus, based on our pilot study, spin rate measurement was not reliable and therefore not valid. Therefore, we believe that ball velocity was the most accurate and valid directly measured variable available to us for driving performance of golfers. Second, golfers used their own drivers in the testing. Differences in length, material, shape of club head, and inertial properties might all affect the ball velocity. Third, the leading arm angle, which was the projection of the leading arm segment on the frontal plane, did not describe the 3-degrees-of-freedom rotational kinematics of the glenohumeral joint, and was isolated from the context of the trunk movements. Without the knowledge of how the arm moved with the body, the interpretation of this variable was difficult. Mitchell and colleagues (Mitchell, Banks, Morgan, & Sugaya, 2003) reported the range of motion of the glenohumeral joints during the golf swing, and Zheng et al. (2008) reported the shoulders abduction angles at selected events during the golf swing. Further research applying an improved human body model may fill this gap of knowledge. Fourth, with 308 participants and 22 independent variables, we had a participant-to-variable ratio of 14:1. Several guidelines exist regarding this ratio for multiple regression; for example, Pedhazur (1997) proposed 15:1 or above if generalization is critical. We were aware that our number was lower than the guideline and this may compromise the generalizability, although the power analysis suggested that our number of participants was sufficient for 22 variables. Finally, like most sports biomechanics studies, variables were measured at specific events in a discrete manner. Discrete measurements, however, may fail to capture some key features of the golf swing. In future studies, techniques comparing time series, such as cross correlation (Li & Caldwell, 1999), may be used to identify the pattern-wise differences among golfers of different performance.

In conclusion, we investigated the effects of kinematic and ground reaction force variables on driving ball velocity. Biomechanical variables from previous golf research and coaching ideas were verified. The results of this study may serve as both skill and strength training guidelines for golfers.

References

Adlington, G. S. (1996). Proper swing technique and biomechanics of golf. *Clinics in Sports Medicine*, *15*, 9–26.

Ball, K. A., & Best, R. J. (2007). Different centre of pressure patterns within the golf stroke I: Cluster analysis. *Journal of Sports Sciences*, *25*, 757–770.

Bechler, J. R., Jobe, F. W., Pink, M., Perry, J., & Ruwe, P. A. (1995). Electromyographic analysis of the hip and knee during the golf swing. *Clinical Journal of Sport Medicine*, *5*, 162–166.

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*, 165–176.

Cheetham, P. J., Martin, P. E., & Mottram, R. E. (2000). The importance of stretching the X Factor in the golf downswing. *Paper presented at the International Congress on Sport Science, Sports Medicine and Physical Education.*, Brisbane, QLD, 7–12 September.

Cooper, M. A. J., & Mather, J. S. B. (1994). Categorisation of golf swings. In A. J. Cochran & M. R. Farrally (Eds.), *Science and golf II: Proceedings of the 1994 World Scientific Congress of Golf* (pp. 65–70). London: Taylor & Francis.

Egret, C. I., Nicholle, B., Dujardin, F. H., Weber, J., & Chollet, D. (2006). Kinematic analysis of the golf swing in men and women experienced golfers. *International Journal of Sports Medicine*, *27*, 463–467.

Ehara, Y. (2002). *Comparison meeting of motion analysis systems* Retrieved 22 October, 2009, from http://www.ne.jp/asahi/gaitober/analysis/comparison2002/index-eng.html.

Farrally, M. R., Cochran, A. J., Crews, D. J., Hurdzan, M. J., Price, R. J., Snow, J. T. et al. (2003). Golf science research at the beginning of the twenty-first century. *Journal of Sports Sciences*, *21*, 753–765.

Fradkin, A. J., Sherman, C. A., & Finch, C. F. (2004). How well does club head speed correlate with golf handicaps? *Journal of Science and Medicine in Sport*, *7*, 465–472.

Gatt, C. J., Jr., Pavol, M. J., Parker, R. D., & Grabiner, M. D. (1998). Three-dimensional knee joint kinetics during a golf swing: Influences of skill level and footwear. *American Journal of Sports Medicine*, *26*, 285–294.

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

Jackson, K. M. (1979). Fitting of mathematical functions to biomechanical data. *IEEE Transactions on Biomedical Engineering*, *26*, 122–124.

Jorgensen, T. P. (1994). *The physics of golf.* New York: AIP Press.

Kawashima, K., Meshizuka, T., & Takeshita, S. (1999). A kinematic analysis of foot force exerted on the soles during the golf swing among skilled and unskilled golfers. In M. R. Farrally & A. J. Cochran (Eds.), *Science and golf III: Proceedings of the World Scientific Congress of Golf* (pp. 40–45). Champaign, IL: Human Kinetics.

Koenig, G., Tamres, M., & Mann, R. W. (1994). The biomechanics of the shoe–ground interaction in golf. In A. J. Cochran & M. R. Farrally (Eds.), *Science and golf II: Proceedings of the 1994 World Scientific Congress of Golf* (pp. 40–45). London: Taylor & Francis.

Lephart, S. M., Smoliga, J. M., Myers, J. B., Sell, T. C., & Tsai, Y. S. (2007). An 8-week golf specific exercise program improves physical characteristics, swing mechanics, and golf performance in recreational golfers. *Journal of Strength and Conditioning Research*, *21*, 860–869.

Li, L., & Caldwell, G. E. (1999). Coefficient of cross correlation and the time domain correspondence. *Journal of Electromyography and Kinesiology*, *9*, 385–389.

McHardy, A., Pollard, H., & Luo, K. (2006). Golf injuries: A review of the literature. *Sports Medicine*, *36*, 171–187.

McLean, J. (1992). Widen the gap. *Golf Magazine*, *12*, 49–53.

McTeigue, M., Lamb, S. R., & Mottram, R. (1994). Spine and hip motion analysis during the golf swing. In A. J. Cochran & M. R. Farrally (Eds.), *Science and golf II: Proceedings of the 1994 World Scientific Congress of Golf* (pp. 50–57). London: Taylor & Francis.

Milburn, P. D. (1982). Summation of segmental velocities in the golf swing. *Medicine and Science in Sports and Exercise*, *14*, 60–64.

Mitchell, K., Banks, S., Morgan, D., & Sugaya, H. (2003). Shoulder motions during the golf swing in male amateur golfers. *Journal of Orthopaedic and Sports Physical Therapy*, *33*, 196–203.

Miura, K. (2001). Parametric acceleration – the effect of inward pull of the golf club at impact stage. *Sports Engineering*, *4*, 75–86.

Myers, J., Lephart, S., Tsai, Y., Sell, T., Smoliga, J., & Jolly, J. (2008). The role of upper torso and pelvis rotation in driving performance during the golf swing. *Journal of Sports Sciences*, *26*, 181–188.

Okuda, I., Armstrong, C. W., Tsunezumi, H., & Yoshiike, H. (2002). Biomechanical analysis of professional golfer's swing: Hidemichi Tanaka. In E. Thain (Ed.), *Science and golf IV: Proceedings of the World Scientific Congress of Golf* (pp. 18–27). London: Routledge.

Pedhazur, E. J. (1997). *Multiple regression in behavioral research: Explanation and prediction.* Fort Worth, TX: Harcourt Brace College Publishers.

Penner, A. R. (2003). The physics of golf. *Reports on Progress in Physics*, *66*, 131–171.

Pickering, W. M., & Vickers, G. T. (1999). On the double pendulum model of the golf swing. *Sports Engineering*, *2*, 161–172.

Pink, M., Perry, J., & Jobe, F. W. (1993). Electromyographic analysis of the trunk in golfers. *American Journal of Sports Medicine*, *21*, 385–388.

Reyes, M. G., & Mittendorf, A. (1998). A mathematical swing model for a long-driving champion. In M. R. Farrally & A. J. Cochran (Eds.), *Science and golf III: Proceedings of the World Scientific Congress of Golf* (pp. 13–19). Champaign, IL: Human Kinetics.

Robinson, R. L. (1994). A study of the correlation between swing characteristics and club head velocity. In A. J. Cochran & M. R. Farrally (Eds.), *Science and golf II: Proceedings of the 1994 World Scientific Congress of Golf* (pp. 84–90). London: Taylor & Francis.

Shamus, E., & Shamus, J. (2001). *Sports injury: Prevention and rehabilitation.* New York,: McGraw-Hill.

Sprigings, E. J., & Mackenzie, S. J. (2002). Examining the delayed release in the golf swing using computer simulation. *Sports Engineering*, *5*, 23–32.

Sprigings, E. J., & Neal, R. J. (2000). An insight into the importance of wrist torque in driving the golf ball: A simulation study. *Journal of Applied Biomechanics*, *16*, 356–366.

Wallace, E. S., Graham, D., & Bleakley, E. W. (1990). Foot-to-ground pressure patterns during the golf drive: A case study involving a low handicap player and a high handicap player. In A. J. Cochran (Ed.), *Science and golf: Proceedings of the First World Scientific Congress of Golf* (pp. 25–29). London: E & FN Spon.

Watanabe, K., Kuroki, S., Hokari, M., & Nishizawa, S. (1998). Golf swing and skill. In M. R. Farrally & A. J. Cochran (Eds.), *Science and golf III: Proceedings of the World Scientific Congress of Golf* (pp. 29–39). Champaign, IL: Human Kinetics.

Zheng, N., Barrentine, S. W., Fleisig, G. S., & Andrews, J. R. (2008). Kinematic analysis of swing in pro and amateur golfers. *International Journal of Sports Medicine*, *29*, 487–493.