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# The role of upper torso and pelvis rotation in driving performance during the golf swing

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**Abstract**

While the role of the upper torso and pelvis in driving performance is anecdotally appreciated by golf instructors, their actual biomechanical role is unclear. The aims of this study were to describe upper torso and pelvis rotation and velocity during the golf swing and determine their role in ball velocity. One hundred recreational golfers underwent a biomechanical golf swing analysis using their own driver. Upper torso and pelvic rotation and velocity, and torso-pelvic separation and velocity, were measured for each swing. Ball velocity was assessed with a golf launch monitor. Group differences (groups based on ball velocity) and moderate relationships ($r \geq 0.50$; $P < 0.001$) were observed between an increase in ball velocity and the following variables: increased torso – pelvic separation at the top of the swing, maximum torso – pelvic separation, maximum upper torso rotation velocity, upper torso rotational velocity at lead arm parallel and last 40 ms before impact, maximum torso – pelvic separation velocity and torso – pelvic separation velocity at both lead arm parallel and at the last 40 ms before impact. Torso – pelvic separation contributes to greater upper torso rotation velocity and torso – pelvic separation velocity during the downswing, ultimately contributing to greater ball velocity. Golf instructors can consider increasing ball velocity by maximizing separation between the upper torso and pelvis at the top of and initiation of the downswing.

**Keywords:** *Golf, swing mechanics, biomechanics, kinematics*

## Introduction

The current teaching philosophy of the golf swing emphasizes an increase in torso coiling during the backswing, which theoretically results in increased impulse during the downswing, and subsequent increased ball velocity and ball flight distance. In proficient golfers, the backswing is initiated by simultaneous rotation of the upper torso, upper extremities (arms, wrists, and hands), and club away from the address position, followed immediately by some degree of pelvic rotation (Hogan & Wind, 1957; McTeigue, Lamb, Mottram, & Pirozzolo, 1994). The order of events during the downswing includes initiating pelvic rotation back towards the impact position, immediately followed by upper torso rotation, and movement of the arms, wrists, hands, and club (Hogan & Wind, 1957; McTeigue *et al.*, 1994).

Often, teaching professionals seek to maximize upper torso rotation during the backswing while minimizing pelvic rotation in their students, creating torso – pelvic separation. Potentially, this creates resistance between the upper torso and pelvis during the backswing, increasing the stored energy, which is released during the downswing. The release of stored energy results in more impulse and increased club head speed, ball velocity, and therefore driving distance. Teaching professionals often describe this separation between the upper torso and pelvis rotation as "x-factor" or "segment separation", which is specifically defined as the difference in axial rotation between the upper torso and pelvis at the top of the backswing (McLean & Andrisani, 1997). It is believed that maximizing torso – pelvic separation will contribute to increased ball velocity and driving distance and as such has recently been described as "the secret power move to add 25

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yards'' (Kostis & Midland, 2006). The ''x-factor stretch'' has been described as the maximum torso – pelvic separation that occurs during the downswing and is suggested to result from initiation of the downswing with the pelvis rotating back towards the impact position while the upper torso is still rotating towards the top of the backswing, creating maximum separation between the segments (McLean & Andrisani, 1997). Burden and colleagues (Burden, Grimshaw, & Wallace, 1998) demonstrated that skilled golfers (sub-10 handicap) perform this countermovement of the pelvis and upper torso at the start of the downswing. They further describe how the countermovement of the pelvis and upper torso create a summation of speed that ultimately results in greater force being applied by the club to the ball at impact.

From a biomechanics perspective, this belief that torso – pelvic separation is an important contributor to increasing driving distance has merit. The action of the torso during the golf swing can be classified as a stretch – shortening movement (Fletcher & Hartwell, 2004). Movements that involve a stretch – shortening contraction utilize stretching active muscles (eccentric loading) to load the muscle in order to increase power output during the final phase of the movement (concentric shortening) (Komi, 1984, 2000; Norman & Komi, 1979). Ultimately, a muscle that is eccentrically loaded before a concentric contraction results in increased force and power production compared with an isolated concentric or eccentric muscle contraction (Ettema, Huijing, & De Haan, 1992; Ettema, Huijing, Van Ingen Schenau, & De Haan, 1990a; Ettema, Van Soest, & Huijing, 1990b). The increased force production is a result of utilization of elastic energy within the muscle – tendon unit during the eccentric loading of the active muscle that is released during the concentric phase of the movement. (Finni, Ikegawa, Lepola, & Komi, 2003; Komi, 2000).

We can potentially apply these stretch – shortening principles to the golf swing. Electromyography studies have demonstrated that the trunk muscles including erector spinae, abdominal obliques, rectus abdominis, latissimus dorsi, and gluteals are active during the backswing (Horton, Lindsay, & Macintosh, 2001; Pink, Jobe, & Perry, 1990; Pink, Perry, & Jobe, 1993; Watkins, Uppal, Perry, Pink, & Dinsay, 1996). Additionally, during the backswing, separation between the upper torso and pelvis results in stretching (eccentric loading) of these activated trunk muscles, which could ultimately contribute to the powerful concentric trunk muscle contractions needed to drive the ball. These activated muscles play a significant role in generating club head speed during the downswing (Horton *et al.*, 2001; Pink *et al.*, 1990, 1993; Watkins *et al.*, 1996). Thus, it is hypothesized that as this separation between the upper torso and pelvic rotation increases, the resulting increase in concentric contraction during the golf swing will increase club head speed, resulting in increased ball velocity and driving distance.

While individuals who teach and study the golf swing anecdotally appreciate the important role that the upper torso and pelvis play in increasing ball velocity and driving distance, the biomechanical role of the upper torso and pelvis rotation and resulting driving performance characteristics has not been scientifically described. To date, there is little peer-reviewed published research that describes the role of upper torso and pelvis rotation in generating driving performance. In the present study, ball velocity was the variable we used to represent driving performance. The aims of the study were to describe upper torso and pelvis rotation and velocity during the golf swing and determine their role in ball velocity. The study provides golf instructors, clinicians, and researchers with a description of the upper torso and pelvis during the golf swing and their role in generating ball velocity, in the hope of applying the results to how the swing is taught.

## Methods

### *Participants*

One hundred recreational golfers participated in the study. All participants had a United States Golf Association registered handicap. Complete participant demographics are given in Table I. All participants were free of injury and had no significant history of joint injury at the time of testing. All participants provided informed consent as required by the university's institutional review board.

### *Instrumentation*

Kinematic data of the golf swing were collected using the Peak Motus System v.8.2 (Peak Performance Technologies, Inc., Englewood, CO). This is a three-dimensional motion analysis system with eight optical cameras that surround the golfer, each placed at a distance of 4 m from the golf teeing area. A sampling rate of 200 frames per second was used in this study. Calibration was done using the wand calibration method according to the manufacturer's guidelines. Our laboratory has established both the position and orientation error of our system, resulting in root mean square error of 0.002 m and 0.254° respectively.

Ball flight characteristics were assessed with the Flight Scope Sim Sensor (EDH, Ltd., South Africa) integrated with AboutGolf (AboutGolf Limited, Maumee, OH) simulation software. The Flight

Table I. Demographics of the participants (mean ± *s*).

| | Age (years) | Stature (m) | Body mass (kg) | USGA handicap index |
|---|---|---|---|---|
| All golfers ($n = 100$) | 45.1 ± 15.9 | 1.80 ± 0.07 | 86.5 ± 14.0 | 8.1 ± 7.3 |
| Golfers with low ball velocity ($n = 21$) | 58.5 ± 13.7 | 1.79 ± 0.08 | 85.1 ± 11.5 | 15.1 ± 5.2 |
| Golfers with medium ball velocity ($n = 65$) | 44.6 ± 14.9 | 1.80 ± 0.07 | 86.7 ± 14.8 | 7.8 ± 6.9 |
| Golfers with high ball velocity ($n = 14$) | 33.1 ± 11.4 | 1.82 ± 0.05 | 87.4 ± 13.4 | 1.8 ± 3.2 |

Scope Sim Sensor applies three-dimensional phased-array microwave technology that operates at 7 kHz to track ball flight from club impact until impact with a screen 5 m away. Ball velocity, vertical launch angle, horizontal launch angle, spin rates, carry distance, and total distance are derived from ball tracking data. The variable of interest in the current study was ball velocity given that this variable is measured directly by the ball flight sensor from the point of ball impact until the ball hits the protective backstop.

*Procedures*

Each participant attended one test session. Participants were fitted with retroreflective markers (0.025 m diameter) on the sacrum and seventh cervical vertebra as well as bilaterally on the anterior superior iliac spine, acromion, and lateral epicondyle of the humerus. In addition to the lateral epicondyle markers, two markers were placed on the golf club to identify the phases of the golf swing (Figure 1).

Each participant was instructed to warm up before data collection at their own discretion. Common modes of warm-up included but were not limited to cardiovascular warm-up on a treadmill or exercise bike, stretching, the swinging of weighted clubs or training devices, and hitting practice shots with the club of the participant's choosing. Data collection consisted of each participant hitting the same brand of golf ball (Titleist, Acushnet Co., Acushnet, MA) with their own driver to represent the swing and ball flight patterns experienced while playing. Participants hit 10 shots off an artificial turf tee box into a projected practice range image on the screen (backstop) while both kinematics of the golf swing and ball flight characteristics were collected.

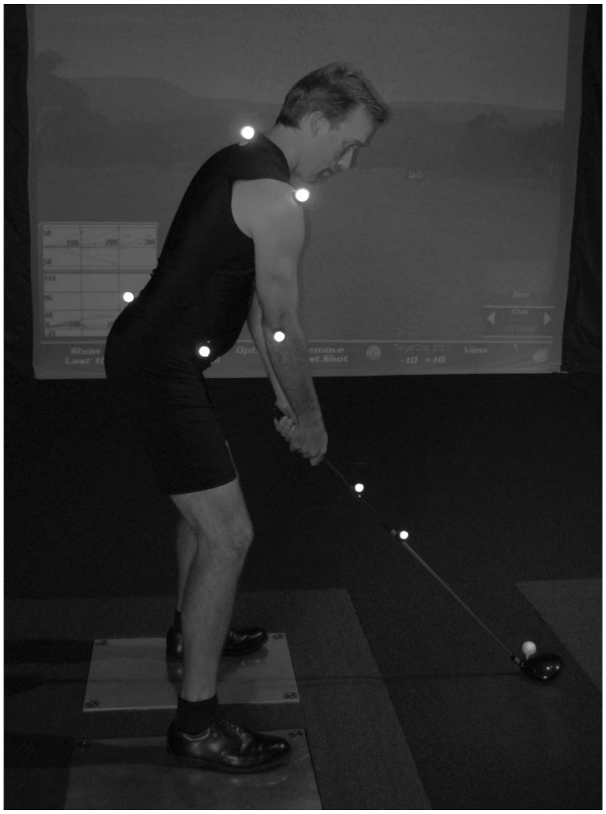

Figure 1. The retroreflective marker configuration utilized for motion analysis of the golf swing. Permission was obtained from the participant to reproduce this image.

*Data reduction*

While each participant hit 10 shots, only the five shots with the highest ball velocity were reduced and analysed. The swing points of interest, including top of the swing, lead arm parallel during the downswing, the point at the last 40 ms before impact, and impact, were determined from the position of the club and upper extremity markers. Top of the swing was calculated as the point when the club markers change direction (along all global axes) at the end of the backswing. Lead arm parallel was the instant during the downswing where a vector connecting the shoulder marker and the elbow marker is parallel to the horizontal plane of the global coordinate system. Impact was the point when the club makes contact with the ball and was identified with a view camera that was synchronized with the kinematic collection cameras and verified with club coordinate data. The last 40 ms point was defined as eight frames before the impact point given the sampling frequency was 200 frames per second. Miura (2001) described the last 40 ms before impact to be an important instant during the swing because much of the momentum generated by the body is imparted on the club at this time. The raw coordinate data collected from each camera were filtered using an optimized cut-off frequency and used to calculate the kinematic data (Jackson, 1979). Upper torso rotation and pelvis rotation angles were calculated as the angle between the respective segment and the global x-axis. The global x-axis was set up so that a neutral address position of the upper torso and pelvis would be zero degrees (Figure 2). The torso – pelvic separation variable was calculated as the difference between the pelvic rotation angle and upper torso rotation angle and at the top of the backswing (Figure 2). Maximum torso – pelvic separation was defined as the maximum difference between the upper torso rotation angle and pelvic rotation angle that occurred during the downswing and is representative of "x-factor stretch" described in the golf instruction literature (McLean & Andrisani, 1997) . In the current study, the torso – pelvic separation is represented by a negative number, since the upper torso rotation commonly exceeds pelvic rotation. As such, more separation between the two segments will be represented by a more negative value. Upper torso and pelvic rotational velocity was defined as the rate of change of the rotation angle with respect to time. Torso – pelvic separation velocity was defined as the rate of change of the separation with respect to time. A negative torso – pelvic separation velocity represents coiling, while a positive torso – pelvic separation velocity represents uncoiling. The mean of the five shots reduced for data analysis was recorded for statistical analysis.

### *Statistical analysis*

At the end of data collection, the 100 golfers was stratified according to their ball velocity. The group mean and standard deviation of the entire group's ball velocity was calculated. Group stratifications were based on descriptive data and groups were defined based on whether individual ball velocity fell below the group mean minus the standard deviation (a group of golfers with low ball velocity), above the mean plus standard deviation (a group of golfers with high ball velocity) or within the window of the mean ± standard deviation (a group of golfers with medium ball velocity). Group demographics are given in Table I. Group comparisons were made using one-way analyses of variance (ANOVA) with *post-hoc* Bonferroni correction analyses. Pearson pairwise correlations were also used to examine further the relationships between ball velocity and upper torso and pelvic rotation angles and velocities measured. All statistical assumptions underlying the use of parametric procedures were checked and verified. All statistical analyses were performed with the SPSS v.11.0 (SPSS Inc, Chicago IL) statistical software package. An alpha level of 0.05 was set *a priori* for statistical analyses.

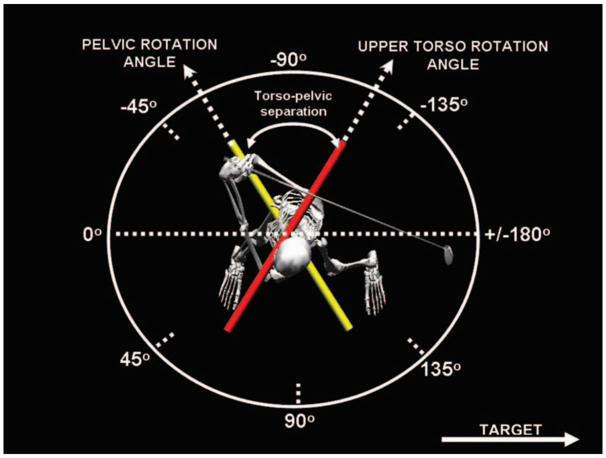

Figure 2. Definition of the upper torso rotation, pelvic rotation, and torso – pelvic separation angles assessed.

## Results

The mean ball velocity for the entire group was 64.9 $\mathrm{m \cdot s^{-1}}$ ($s = 6.8$). From these data, group stratifications included a group of golfers ($n = 21$) with low ball velocity ($< 58.1\ \mathrm{m \cdot s^{-1}}$ [$64.9 - 6.8 = 58.1$]), a group ($n = 14$) with high ball velocity ($> 71.8\ \mathrm{m \cdot s^{-1}}$ [$64.9 + 6.8 = 71.8$]), and a group ($n = 65$) with medium ball velocity within the window of the mean ± standard deviation (58.1 – 71.8 $\mathrm{m \cdot s^{-1}}$). Stratified group demographics are provided in Table I. The means, standard deviations, and notation of group statistical differences (based on the ANOVA with Bonferroni *post-hoc* analyses) for each of the variables assessed are presented in Table II. Group differences were observed for torso – pelvic separation at the top of the swing, maximum torso – pelvic separation, upper torso rotation velocity at lead arm parallel and last 40 ms before impact, maximum upper torso velocity, pelvic rotation at the top of swing, lead arm parallel and last 40 ms before impact, maximum pelvic rotation velocity, torso – pelvic separation velocity lead arm parallel and last 40 ms before impact, and maximum torso – pelvic separation velocity.

The correlation coefficients and level of significance for all comparisons are given in Table III. A moderate positive correlation was observed between ball velocity and torso – pelvic separation at the top of the swing, maximum torso – pelvic separation, maximum upper torso rotational velocity, upper torso rotational velocity at lead arm parallel and last 40 ms before impact, maximum torso – pelvic separation velocity, and torso – pelvic separation velocity at both lead arm parallel and last 40 ms before impact.

Table II. Swing mechanics descriptive statistics (mean ± *s*).

| | Low ball velocity | Medium ball velocity | High ball velocity | *P* |
|---|---|---|---|---|
| Ball velocity (m · s$^{-1}$) | 55.7 ± 2.7 | 65.6 ± 3.7 | 75.4 ± 4.4 | <0.0001[a] |
| Upper torso rotation at top of swing (°) | −94.0 ± 13.5 | −97.0 ± 20.2 | −104.0 ± 10.3 | 0.264 |
| Upper torso rotation at lead arm parallel (°) | −36.1 ± 9.1 | −39.6 ± 15.9 | −37.4 ± 9.4 | 0.588 |
| Upper torso rotation at last 40 ms before impact (°) | 0.0 ± 10.0 | −0.2 ± 16.2 | 2.3 ± 7.2 | 0.835 |
| Upper torso rotation at impact (°) | 20.3 ± 10.2 | 22.8 ± 16.1 | 25.2 ± 8.9 | 0.600 |
| Maximum upper torso rotation (°) | −95.4 ± 13.2 | −98.3 ± 19.9 | −106.1 ± 10.6 | 0.201 |
| Pelvic rotation at top of swing (°) | −49.8 ± 11.4 | −47.5 ± 17.4 | −44.9 ± 10.3 | 0.660 |
| Pelvic rotation at lead arm parallel (°) | −4.3 ± 7.4 | −1.3 ± 16.6 | 6.4 ± 7.2 | 0.087 |
| Pelvic rotation at last 40 ms before impact (°) | 17.8 ± 8.1 | 22.4 ± 16.9 | 26.8 ± 6.7 | 0.190 |
| Pelvic rotation at impact (°) | 29.4 ± 8.6 | 35.3 ± 17.0 | 38.3 ± 7.2 | 0.163 |
| Maximum pelvic rotation (°) | −53.2 ± 10.6 | −51.3 ± 16.5 | −50.4 ± 10.1 | 0.210 |
| Torso–pelvic separation at top of swing (°) | −44.2 ± 7.7 | −49.5 ± 9.6 | −59.1 ± 8.2 | <0.0001[b,c] |
| Maximum torso–pelvic separation (°) | −45.6 ± 8.0 | −51.7 ± 10.3 | −61.8 ± 7.8 | <0.0001[a] |
| Upper torso rotation velocity at top of swing (° · s$^{-1}$) | 48.8 ± 55.5 | 54.4 ± 62.6 | 79.6 ± 56.2 | 0.296 |
| Upper torso rotation velocity at lead arm parallel (° · s$^{-1}$) | 546.1 ± 61.6 | 625.6 ± 99.0 | 738.3 ± 79.2 | <0.0001[a] |
| Upper torso rotation velocity at last 40 ms before impact (° · s$^{-1}$) | 515.5 ± 72.2 | 603.3 ± 76.3 | 637.9 ± 81.7 | <0.0001[b,d] |
| Upper torso rotation velocity at impact (° · s$^{-1}$) | 498.7 ± 123.5 | 539.1 ± 98.8 | 520.1 ± 117.1 | 0.321 |
| Maximum upper torso rotation velocity (° · s$^{-1}$) | 591.2 ± 66.8 | 675.1 ± 84.4 | 766.6 ± 73.0 | <0.0001[a] |
| Pelvic rotation velocity at top of swing (° · s$^{-1}$) | 74.8 ± 57.9 | 96.3 ± 59.7 | 128.7 ± 52.4 | 0.032[b] |
| Pelvic rotation velocity at lead arm parallel (° · s$^{-1}$) | 348.8 ± 59.9 | 395.4 ± 67.2 | 401.7 ± 67.5 | 0.015[d] |
| Pelvic rotation velocity at last 40 ms before impact (° · s$^{-1}$) | 310.2 ± 63.4 | 349.8 ± 58.5 | 318.7 ± 72.4 | 0.021[d] |
| Pelvic rotation velocity at impact (° · s$^{-1}$) | 258.8 ± 65.7 | 277.4 ± 67.0 | 248.5 ± 82.9 | 0.270 |
| Maximum pelvic rotation velocity (° · s$^{-1}$) | 357.6 ± 58.3 | 410.4 ± 66.4 | 433.6 ± 90.9 | 0.003[b,d] |
| Torso–pelvic separation velocity at top of swing (° · s$^{-1}$) | −26.0 ± 27.2 | −41.9 ± 37.1 | −49.1 ± 31.2 | 0.104 |
| Torso–pelvic separation velocity at lead arm parallel (° · s$^{-1}$) | 197.3 ± 47.7 | 230.2 ± 68.4 | 336.6 ± 69.9 | <0.0001[b,c] |
| Torso–pelvic separation velocity at last 40 ms before impact (° · s$^{-1}$) | 205.4 ± 47.0 | 253.4 ± 66.9 | 319.2 ± 65.6 | <0.0001[a] |
| Torso–pelvic separation velocity at impact (° · s$^{-1}$) | 239.9 ± 86.6 | 261.7 ± 70.6 | 271.6 ± 86.0 | 0.416 |
| Maximum torso–pelvic separation velocity (° · s$^{-1}$) | 278.1 ± 46.6 | 311.8 ± 60.3 | 389.6 ± 55.6 | <0.0001[b,c] |

[a] All three groups significantly different.
[b] Low ball velocity group significantly different vs. high ball velocity group.
[c] Medium ball velocity group significantly different vs. high ball velocity group.
[d] Low ball velocity group significantly different vs. medium ball velocity group.

Table III. Correlation coefficients between ball velocity and the upper torso and pelvic rotation variables assessed.

| | Maximum | Top of swing | Lead arm parallel | Last 40 ms before impact | Impact |
|---|---|---|---|---|---|
| Torso–pelvic separation | **−0.54 (*P* < 0.001)** | **−0.55 (*P* < 0.001)** | N.A. | N.A. | N.A. |
| Upper torso rotation | N.A. | −0.19 (*P* = 0.056) | −0.10 (*P* = 0.324) | 0.01 (*P* = 0.959) | 0.07 (*P* = 0.467) |
| Pelvic rotation | N.A. | 0.13 (*P* = 0.189) | 0.23 (*P* = 0.023) | 0.21 (*P* = 0.041) | 0.20 (*P* = 0.042) |
| Upper torso rotational velocity | **0.59 (*P* < 0.001)** | 0.23 (*P* = 0.025) | **0.61 (*P* < 0.001)** | **0.50 (*P* < 0.001)** | 0.06 (*P* = 0.536) |
| Pelvic rotational velocity | 0.36 (*P* < 0.001) | 0.35 (*P* < 0.001) | 0.32 (*P* < 0.001) | 0.08 (*P* = 0.439) | −0.05 (*P* = 0.604) |
| Torso–pelvic separation velocity | **0.50 (*P* < 0.001)** | −0.21 (*P* = 0.041) | **0.55 (*P* < 0.001)** | **0.53 (*P* < 0.001)** | 0.14 (*P* = 0.178) |

*Note*: Moderate relationships ($r > 0.5$) are shown in **bold** font. N.A. = not applicable.

## Discussion

The aims of this study were to examine the relationship between ball velocity, upper torso rotation position and velocity, pelvis rotation position and velocity, and torso–pelvic separation position and velocity measured during the golf swing, and determine whether the upper torso and pelvic variables differed between groups stratified by ball velocity. The results indicate that the magnitude of upper torso and pelvic rotation position does not make a significant contribution to ball velocity; rather, it is the separation between the two segments that appears to be most important contributor given the group differences and moderate relationship that was observed between torso–pelvic separation (at top of swing and maximum) and ball velocity. Thus, if a golfer increases upper torso rotation at the top of the golf swing to increase ball velocity, it would be most effective to do so while limiting the amount of pelvic rotation, thereby increasing separation between the two segments.

Theoretically, this greater separation could result in eccentric loading of the torso musculature through lengthening (Fletcher & Hartwell, 2004). This eccentric loading potentially could lead to faster uncoiling velocity during the downswing, thereby contributing to increased ball velocity. Additionally, the greater separation between segments might allow increased time for force to be applied to the club, resulting in greater impulse. Thus, there is the potential to increase momentum of the club and ultimately increase club velocity. In the current study, both torso–pelvic velocity (which represents the how quickly the golfer uncoils during the downswing) and upper torso rotational velocity during the downswing (maximum, at lead arm parallel, and last 40 ms before impact) differed between the highest ball velocity and lowest ball velocity groups and was correlated with increased ball velocity. Additionally, the segment velocities during the downswing were faster in the high ball velocity groups. Therefore, golf instruction or a golf fitness training programme that increases torso–pelvic separation could increase upper torso rotation velocity and consequentially ball velocity. It has previously been demonstrated that a golf-specific training programme that focuses on increasing core stability strength and torso flexibility increases torso–pelvic separation, ball velocity, and carry distance by approximately 6% in a group of amateur golfers (Lephart, Smoliga, Myers, Sell, & Tsai, 2007). Interestingly, none of the pelvic rotation position or velocity variables correlated with increased ball velocity. These results suggest that the upper torso might play a more important role in creating torso–pelvic separation and the subsequent increase in ball velocity through both increasing uncoiling (torso–pelvic separation velocity) and upper torso rotational velocity during the downswing. Group differences were present in pelvic rotational velocity, but are possibly unrelated to ball velocity given the lack of correlation. None of the variables assessed differed by group or were correlated with increased ball velocity at the instant of ball impact. There is a potential at impact that the club head–ball interaction plays more of a role in affecting ball velocity, and the torso–pelvis deceleration that is present might be associated with the transfer of momentum from the torso to the club (Burden *et al.*, 1998; McTeigue *et al.*, 1994; Penner, 2003).

Other researchers have assessed the role of the torso and pelvis in the golf swing, reporting similar findings to the current study. McTeigue and colleagues (1994) analysed the three-dimensional motion of the spine and hips during the golf swing. As in the current study, McTeigue *et al.* found that the torso and pelvis position were less important than the separation between the two segments (torso–pelvic separation). Their results demonstrated that professional Tour players who have long driving distances tended to have increased separation between the upper torso and pelvic segments. It was hypothesized that the increased separation was a result of the pelvis starting the downswing while the torso continued to rotate away from the target (maximum torso–pelvic separation). Cheetham and colleagues (Cheetham, Martin, Mottram, & Laurent, 2000) reported that touring professionals demonstrated increased torso–pelvic separation at both the top of the swing and maximum torso–pelvic separation compared with amateur golfers, and that maximum torso–pelvic separation is considered more important for increased driving distance. In line with the results of Cheetham *et al.* (2000), our findings demonstrate the importance of both maximum torso–pelvic separation and torso–pelvic separation at the top of the swing in driving performance. However, our results do not support the conclusion of Cheetham *et al.* (2000) that maximum torso–pelvic separation plays more of a role than torso–pelvic separation at the top of the swing. In the current study, both maximum torso–pelvic separation and torso–pelvic separation equally correlated with our measure of driving performance (ball velocity) and differed between groups. Burden *et al.* (1998) described torso and pelvis rotations in single-digit handicap golfers, reporting that the sequencing of the torso and pelvic movement plays a significant role in summating the forces from the proximal trunk to the distal aspect of the club. Our results support these findings by demonstrating that torso–pelvic separation (both maximum and at the top of the swing) may contribute to increased uncoiling velocity (upper torso and torso–pelvic separation velocity) of the trunk during the downswing, ultimately contributing to increased ball velocity.

We acknowledge some limitations to the current study. Driving performance was limited to measuring ball velocity within an indoor laboratory facility. Variables of interest to most golfers (carry and total driving distance) could only be estimated. Thus, we opted to examine ball velocity only given that this variable was directly measured during testing. Driving distance depends not only on ball velocity, but other factors including launch angle, ball drag, and spin rate (Penner, 2003). If launch angle, ball drag, and/or spin rate remain constant while ball velocity is increased, the ball will fly further, suggesting that ball velocity is the most important variable associated with driving performance. Additionally, club characteristics such as degrees of loft, shaft stiffness, shaft length, and coefficient of restitution of the club face may also affect ball velocity. A second limitation is the research design. In the current study, we only identified relationships and group differences between torso and pelvis rotation variables and ball velocity. A cause – effect mechanism (i.e. increased torso – pelvic separation causes increased ball velocity) was not established. Ultimately, if it could be demonstrated scientifically how torso – pelvic separation can be increased, thereby increasing ball velocity, the results would have dramatic effects on instruction of the golf swing. This is an area of future research. Additionally, this study did not control for the specific driver being used. All participants used their own driver so that ball flight characteristics best represented golf performance. But differences in club characteristics (shaft length and stiffness, material properties of the club head, etc.) could have resulted in higher variability between participants. An additional limitation that warrants discussion is the potential influence of shoulder complex motion on the upper torso rotation angle. In the current study, the torso was modelled as a rigid segment from the markers on the acromions and C7, yet shoulder complex motions like scapular protraction/retraction could potentially influence the vector created between the two acromion markers. Finally, we acknowledge that other statistically significant relationships ($P < 0.05$) existed (see Table III). But in the current study, only relationships with a correlation coefficient greater than or equal to 0.50 (a moderate relationship) were discussed. While other relationships may be statistically significant, significance only indicates the probability of committing a type 1 error for interpreting the minimal relationships.

Our results have direct application to instruction of the golf swing. Instructors of the game who wish to increase ball velocity (and ultimately driving distance) should focus on increasing separation between the upper torso and pelvis (factors that have a direct relationship with ball velocity) given the relationship established in the current study. This can potentially be achieved by increasing the amount of upper torso rotation obtained during the backswing, while maintaining the current amount or possibly limiting the amount of pelvic rotation present. Additionally, torso – pelvic separation can most likely be increased by instructing students to start the downswing with pelvic rotation back towards the target while the upper torso still rotates away, a manoeuvre identified in skilled golfers (Burden *et al.*, 1998; McTeigue *et al.*, 1994). Additionally, a golf fitness programme designed specifically to increase upper torso flexibility and strength could be beneficial in increasing ball velocity and subsequently driving distance by increasing separation between the upper torso and pelvis segments (Lephart *et al.*, 2007).

## Conclusions

A moderate relationship and group differences existed between increased ball velocity and increased torso – pelvic separation at the top of the swing, maximum torso – pelvic separation, maximum upper torso rotation velocity, upper torso rotational velocity at lead arm parallel and last 40 ms before impact, maximum torso – pelvic separation velocity and torso – pelvic separation velocity at both lead arm parallel and last 40 ms before impact. These results suggest that torso – pelvic separation (both maximum and at the top of the swing) contributes to increased upper torso rotation velocity and torso – pelvic separation velocity during the downswing, ultimately contributing to increased ball velocity.

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