

Title: Movement variability in the golf swing of male and female skilled golfers

Running title: Golf swing variability in skilled golfers

Authors and affiliations:

Sean A Horan^{1,2}, Kerrie Evans^{1,2}, Justin J Kavanagh^{1,2}

1. School of Physiotherapy and Exercise Science,
Griffith University,
Australia
2. Musculoskeletal Research Program
Griffith University,
Australia

Corresponding author details:

Sean Horan

School of Physiotherapy and Exercise Science

Gold Coast campus

Griffith University

QLD, AUSTRALIA 4222

Ph: +61 7 5552 8038

Fax: +61 7 5552 8674

Email: s.horan@griffith.edu.au

Disclosure: No funding was received for this work from the National Institutes of Health (NIH); Wellcome Trust; Howard Hughes Medical Institute (HHMI); or any other organization.

ABSTRACT

Background: Despite the complexity of movement, the swings of skilled golfers are considered to be highly consistent. Interestingly, no direct investigation of movement variability or coupling variability during the swings of skilled golfers has occurred.

Purpose: To determine if differences in movement variability exist between male and female skilled golfers during the downswing of the full golf swing. **Methods:** 3D

thorax, pelvis, hand and clubhead data were collected from 19 male (mean \pm SD; age = 26 ± 7 years) and 19 female (age = 25 ± 7 years) skilled golfers. Variability of

segmental movement and clubhead trajectory were examined at three phases of the downswing using discrete (standard deviation) and continuous analyses (spanning

set), while variability of inter-segment coupling was examined using average coefficient of correspondence. **Results:** Compared to males, females exhibited higher

thorax and pelvis variability for axial rotation at the mid-point of the downswing and ball contact (BC). Similarly, thorax-pelvis coupling variability was higher for females

than males at both the mid-point of the downswing and BC. Regardless of thorax and pelvis motion, the variability of hand and clubhead trajectory sequentially decreased

from the top of the backswing to BC for both males and females. **Conclusions:** Male

and female skilled golfers utilise different upper body movement strategies during the downswing while achieving similarly low levels of clubhead trajectory variability at

BC. It is apparent that the priority of skilled golfers is to progressively minimise hand and clubhead trajectory variability towards BC, despite the individual motion or

coupling of the thorax and pelvis. **Key words:** COORDINATION; GENDER DIFFERENCES; GOLF SWING; MOTOR CONTROL.

INTRODUCTION

Paragraph Number 1 The golf swing is a whole body multi-joint movement, and coordinating the many degrees of freedom required to perform the task presents a considerable control challenge. Despite the complexity of the movement, skilled golfers are thought to perform the swing in a consistent manner so that they can strike the ball with repeated accuracy across multiple swings (29). Although the movement of individual body segments is suggested to influence clubhead trajectory during the golf swing (6, 24), the degree of segment and inter-segment movement variability during the swing of skilled male and female golfers is unknown.

Paragraph Number 2 Variability in motor output is an inherent characteristic of the human neuromotor system (19, 25). In multi-joint tasks that require precision of an end-point effector, the variability of individual segment trajectories may be substantially greater than the variability of the end-point trajectory (1, 4, 11). This feature was perhaps best illustrated in the classic study of Bernstein (4), where the movement of professional blacksmiths were described when repeatedly hitting a chisel. Considerable variability was observed for individual joints of the upper body, yet the trajectory of the hammer tip was consistent with each strike, particularly at the point of impact. If similar features of control were evident in the golf swing, the degree of variability of the thorax and pelvis would not necessarily be reflected in hand and clubhead trajectories during the downswing. Instead, segmental movement variability would be organised to ensure consistent hand motion from trial-to-trial, particularly at ball contact (BC) where precision of the clubhead trajectory is most critical (36). Interestingly, the only study to exclusively examine movement variability in skilled and unskilled golfers during the full golf swing did not observe any group differences in variability at top of backswing (TBS) or BC, but did identify

differences in lead wrist angle and trail forearm angle variability at mid-backswing (5). However in this investigation, 3D movement of the golf swing was measured using planar-based video analysis, and only selective trunk, arm and club kinematics were reported. More detailed analysis of the downswing phase, with particular focus on segment and inter-segment movement variability of the pelvis and thorax, along with examination of hand and clubhead trajectory would provide greater insight into movement variability during the golf swing.

Paragraph Number 3 Currently there is no consensus concerning the role of gender in controlling multi-joint tasks that require precision of an end-point effector. Instead, it appears that gender related differences in variability are task specific (28, 31) and may in part be influenced by differences in movement velocity. While 3D thorax and pelvis kinematics of male and female skilled golfers have been shown to be similar during the downswing, gender differences in movement velocity exist (15, 40). In particular, male golfers are able to achieve greater segmental velocity at BC, and greater overall maximum velocity for the thorax and pelvis segments compared to females. Although the relationship between segment velocity and variability is unclear, and yet to be studied for the golf swing, it is possible that the scaling of joint torques that drive the motion of the golf swing are gender-specific and may be reflected by different variability in movement. Gender-related differences in variability may not only be present at the level of segmental movement, but also for coordination between segments during the swing. The importance of thorax-pelvis coordination with respect to performance is emphasized frequently (6, 7, 9, 23, 39), however no investigation into the role of coordination variability in the golf swing has occurred. Analyses of coordination that address the dynamical nature of movement, combined with more common approaches that examine continuous movement at

discrete intervals, are likely to provide greater understanding of the motor control required to perform the golf swing (3, 16).

Paragraph Number 4 The purpose of this study was to determine if differences in movement variability exist between male and female skilled golfers during the downswing. It was hypothesized that skilled female golfers would exhibit greater thorax and pelvis variability, and therefore greater variability in thorax-pelvis coupling than skilled male golfers. It was anticipated that these differences would be least evident at the TBS, and most evident during mid-downswing (MID) and at BC when thorax and pelvis motion have the highest velocity. It was also hypothesized that hand and clubhead trajectory variability would be similar between genders when performing the same goal directed task, and that hand and clubhead trajectory variability would progressively decrease from TBS to MID to BC given that it is at BC when precision of movement is most critical.

METHODS

Subjects

Paragraph Number 5 Nineteen males (mean \pm standard deviation, age = 26 ± 7 yr, handicap = 0.6 ± 1.1) and 19 females (age = 25 ± 7 years, handicap = 1.3 ± 1.6) volunteered to participate in the study. All subjects were either professional or competitive amateur golfers, played golf right-handed, and were free from musculoskeletal injury at the time of testing as determined by an experienced physiotherapist (SH). The professional golfers that volunteered were credited with a handicap of 0 for the purpose of this study. To ensure only highly skilled golfers were recruited, competitive amateur golfers were only included if they had a registered

Australian handicap ≤ 4 . Written informed consent was obtained prior to data collection and all experimental procedures were approved by the Griffith University Human Research Ethics Committee.

Instrumentation and procedures

Paragraph Number 6 The instrumentation and procedures for data collection have been described in detail previously (15). Briefly, retro-reflective markers were attached to the pelvis on the right and left anterior-superior iliac spines and posterior superior iliac spines. Four markers were attached to the thorax over the suprasternal notch, xiphoid process, C7 and T10 spinous processes. Clubhead trajectory was tracked via a marker attached to the subject's driver. To create a local coordinate system for kinematic modelling, markers were attached to the right and left heel of the subject's golf shoes which approximated the calcanei. Three-dimensional marker trajectories were collected at 500 Hz using a 3D Vicon motion analysis system and modelled using BodyBuilder software version 3.6 (Oxford Metrics, Oxford, UK). All other data analyses were performed using custom-designed software in Matlab version 7.8.0 (The MathWorks, Natick, MA). Raw 3D coordinate data were filtered using a zero-lag fourth-order low-pass Butterworth filter. Cut-off frequencies for individual markers were between 6 and 10 Hz, as determined through residual analysis (10) with an r^2 threshold set at 0.85.

Paragraph Number 7 Thorax and pelvis angular displacement was calculated relative to the **local coordinate system** based on the position of the heel markers at ball address. The origin of the **local coordinate system** was the midpoint between the left and right heel markers. The y-axis was a vector directed towards the target and oriented with the two heel markers. The **local coordinate system** z-axis coincided

with the global vertical and the **local coordinate system** x-axis was the cross product of the plane formed between the **local coordinate system** y- and z-axis. In the present study, thorax and pelvis segment definitions were based on International Society of Biomechanics guidelines (38). The origin of our pelvis coordinate system was the midpoint of the two **anterior-superior iliac spine** and two **posterior-superior iliac spine** markers, with the pelvis z-axis directed cephalad, y-axis directed toward the left side of the pelvis, and the x-axis directed **anteriorly**. The thorax coordinate system was represented in the same manner as the pelvis, however the origin of the coordinate system was located at the midpoint of the C7 marker and the marker over the suprasternal notch. Lateral tilt, anterior-posterior tilt, and axial rotation were defined as angular rotation about each segments *x*, *y*, and *z* axes respectively using Euler angles.

Paragraph Number 8 Experimental testing consisted of each golfer hitting five full shots with their own driver from a rubber tee embedded in an artificial turf mat into a net approximately 3 m away. Each golfer was instructed to address the ball in a neutral stance position, imagine they were on a tee, and hit their usual driver shot as far and as straight as possible. To ensure task consistency, two vertical lines were placed 0.5 m apart on the net, and any shot that was not between the vertical lines was considered a mis-trial and another shot was performed.

Data analysis

Paragraph Number 9 Data analysis was based on the downswing phase defined as the period from TBS to BC. TBS was defined as the transition point where the pelvis stops axially rotating away from the target and begins rotating towards the target. **Data for the downswing phase were normalised to 101 points for each**

individual using piecewise cubic spline interpolation, which enabled swing data to be reported as 0-100% of the downswing cycle, and therefore kinematic variability at the discrete events of TBS, MID and BC could be examined (Figure 1). As it was also of interest to examine variability during the phases associated with TBS, MID and BC a further 20% of swing data on either side of the downswing was required to be normalised (Figure 1). Therefore data could be examined from -20% to 120% relative to the downswing.

Paragraph Number 10 Segment movement variability was examined at the discrete events of TBS, MID, and BC. The sample standard deviation was calculated for each subject's five trials in the anterior-posterior tilt, lateral tilt, and axial rotation directions for the thorax and pelvis. Segment movement variability was also examined at three continuous phases: TBS \pm 20%, MID \pm 20%, and BC \pm 20% of the downswing. Thorax and pelvis kinematics were examined across these continuous phases using the spanning set, which is comprised of vectors that describe the possible linear combinations for a system of equations (17, 18, 20). A greater number of linear combinations indicate a greater number of solutions, or greater trial-to-trial variability about a mean ensemble curve (17). The upper and lower standard deviation curves about a mean ensemble curve form the basis of the vectors for analysis, where polynomials are created which characterise these standard deviation curves. In the present study, a 7th order polynomial was found to account for > 99.9% of variance in angular displacement standard deviation curves. The vectors in the spanning set were defined by a vector space mapped from the polynomial coefficients. Coordinate mapping was employed, which allowed the properties of the polynomials to reflect a familiar coordinate system i.e. the characteristics of the standard deviation about the ensemble curve (18, 20). The magnitude of the spanning set was the norm distance

between the vectors created from the polynomial coefficients. A greater magnitude indicates greater distance between the vectors and therefore greater variability.

Paragraph Number 11 Variability in thorax-pelvis coupling across each golfer's five trials was quantified for TBS \pm 20%, MID \pm 20%, and BC \pm 20% using the average coefficient of correspondence. Average coefficient of correspondence examines inter-segment coupling by quantifying the variability of angle-angle data across multiple trials (33). Vectors are generated between successive frames of normalised data, where each vector describes the direction and amplitude of change in relative motion between each data point (33, 35). The average direction and amplitude of each frame-frame vector is combined and averaged over the entire length of the trial to describe the overall vector deviation. Several vector coding techniques encode data with an integer value which describes a kinematic profile, however the ability of average coefficient of correspondence to describe relative motion is enhanced as the ratio scale of trial-to-trial data is preserved. The average coefficient of correspondence calculates a scalar value between 0 and 1, where 1 indicates perfect repeatability of thorax-pelvis coupling.

Statistical analysis

Paragraph Number 12 A between-within two-way repeated measures ANOVA was employed to examine the effect of gender (male and female) and phase (TBS, MID, and BC) on the dependent measures (standard deviation, spanning set, average coefficient of correspondence). While significant main effects of gender and phase were detected for all dependent measures (all p values $<$ 0.03), the relevance of these effects were limited. That is, as data is collapsed across conditions to calculate main effects there were no clear indication where gender differences occurred during

the downswing. Therefore, gender by phase interaction effects with planned contrasts were the basis of the current study's analysis. The mixed model employed in the study accounted for both fixed and random effects, with low Akaike information criterion indicating an appropriately selected model. All statistical analyses were performed using SAS for Windows Version 9.1 (SAS Institute Inc., Cary, NC). The level of significance was set at $p < 0.05$ and effect sizes were reported as Cohen's d (8).

RESULTS

Descriptive data for subjects

Paragraph Number 13 Male golfers were significantly taller (mean \pm standard deviation, male = 1.80 ± 0.05 m, female = 1.67 ± 0.06 m, $F(1,36) = 52.93$, $p < 0.01$), had greater body mass (male = 80.2 ± 9.1 kg, female = 62.2 ± 9.6 kg, $F(1,36) = 34.97$, $p < 0.01$), arm span (male = 1.84 ± 0.05 m, female = 1.69 ± 0.07 m, $F(1,36) = 59.27$, $p < 0.01$), and clubhead speed (male = 49.1 ± 3.6 m.s⁻¹, female = 40.4 ± 3.0 m.s⁻¹, $F(1,36) = 85.80$, $p < 0.01$) compared to the female golfers.

Between-gender differences during the downswing

Paragraph Number 14 Variability in thorax and pelvis motion. In general, pelvis and thorax kinematics were similar for the male and female golfers (Figure 2), however several gender differences in variability emerged throughout the downswing. Female golfers had **significantly** higher thorax axial rotation standard deviation at BC than males ($F(1,37) = 5.97$, $p = 0.02$, $d = 0.81$), and **significantly** higher pelvis axial rotation standard deviation at MID ($F(1,37) = 7.09$, $p = 0.01$, $d = 0.89$) and BC ($F(1,37) = 3.98$, $p = 0.04$, $d = 0.66$) compared to males (Figure 3). Similarly, female

golfers had **significantly** higher thorax axial rotation spanning sets at BC than males ($F(1,37) = 5.75, p = 0.02, d = 0.80$), and **significantly** higher pelvis axial rotation spanning sets at MID ($F(1,37) = 7.21, p = 0.01, d = 0.90$) and BC ($F(1,37) = 3.99, p = 0.04, d = 0.65$) compared to males (Figure 4).

<<Insert Figures 2, 3 & 4>>

Paragraph Number 15 Thorax-pelvis coupling. Patterns of angle-angle data for thorax-pelvis coupling were comparable between genders for axial rotation, however the range of motion was different for the anterior-posterior and lateral tilt directions (Figure 5). Female golfers had **significantly** lower anterior-posterior tilt, lateral tilt, and axial rotation average coefficient of correspondence values at the MID (anterior-posterior tilt: $F(1,37) = 12.13, p < 0.01, d = 1.16$; lateral tilt: $F(1,37) = 6.24, p = 0.01, d = 0.83$; axial rotation: $F(1,37) = 9.26, p = 0.01, d = 1.01$) and BC (anterior-posterior tilt: $F(1,37) = 15.41, p < 0.01, d = 1.31$; lateral tilt: $F(1,37) = 9.12, p < 0.01, d = 1.01$; axial rotation: $F(1,37) = 12.70, p < 0.01, d = 1.09$) phases compared to males.

<<Insert Figure 5>>

Paragraph Number 16 Hand and clubhead trajectory. Gender differences were only observed for the trajectory of the hand, where females exhibited **significantly** higher standard deviation ($F(1,37) = 6.21, p = 0.02, d = 0.83$) and **significantly** higher spanning sets ($F(1,37) = 6.61, p = 0.01, d = 0.86$) at TBS compared to males (Figure 6).

<<Insert Figure 6>>

Within-gender differences during the downswing

Paragraph Number 17 Variability in thorax and pelvis motion. The female golfers had **significantly** increased thorax axial rotation and pelvis axial rotation standard deviations at MID compared to TBS (thorax: $F(1,37) = 7.00$, $p = 0.01$, $d = 0.56$); pelvis: $F(1,37) = 14.66$, $p < 0.01$, $d = 1.00$) (Figure 3). Similarly, females had **significantly** increased thorax axial rotation and pelvis axial rotation spanning sets at MID compared to TBS (thorax: $F(1,37) = 10.87$, $p < 0.01$, $d = 0.66$; pelvis: $F(1,37) = 16.50$, $p < 0.01$, $d = 1.04$) (Figure 4). The male golfers had **significantly** increased thorax axial rotation standard deviation at MID compared to BC ($F(1,37) = 5.48$, $p = 0.02$, $d = 0.60$) and similarly, **significantly** increased thorax axial rotation spanning sets at MID compared to BC ($F(1,37) = 5.06$, $p = 0.03$, $d = 0.57$).

Paragraph Number 18 Thorax-pelvis coupling. Female golfers exhibited **significantly** increased anterior-posterior tilt average coefficient of correspondence values at MID compared to TBS ($F(1,37) = 43.46$, $p < 0.01$, $d = 1.99$) and at BC compared to MID ($F(1,37) = 20.90$, $p < 0.01$, $d = 0.99$) (Figure 5). Females also exhibited **significantly** increased lateral tilt and axial rotation average coefficient of correspondence values at MID compared to TBS (lateral tilt: $F(1,37) = 15.91$, $p < 0.01$, $d = 1.11$; axial rotation: $F(1,37) = 43.04$, $p < 0.01$, $d = 2.06$). Males exhibited **significantly** increased anterior-posterior tilt average coefficient of correspondence values at MID compared to TBS ($F(1,37) = 82.68$, $p < 0.01$, $d = 2.66$) and at BC compared to MID ($F(1,37) = 8.60$, $p < 0.01$, $d = 1.13$). Male golfers also exhibited **significantly** increased lateral tilt and axial rotation average coefficient of

correspondence values at MID compared to TBS (lateral tilt: $F(1,37) = 30.69$, $p < 0.01$, $d = 2.11$; axial rotation: $F(1,37) = 52.78$, $p < 0.01$, $d = 2.10$).

Paragraph Number 19 Hand and clubhead trajectory. Female golfers had **significantly** increased hand trajectory standard deviation at TBS compared to MID ($F(1,37) = 17.27$, $p < 0.01$, $d = 1.08$) and at MID compared to BC ($F(1,37) = 5.00$, $p = 0.03$, $d = 0.54$) (Figure 6). Similarly, females had **significantly** increased hand trajectory spanning sets at TBS compared to MID ($F(1,37) = 20.89$, $p < 0.01$, $d = 1.02$) and at MID compared to BC ($F(1,37) = 8.85$, $p < 0.01$, $d = 0.57$). For the male golfers, **significantly** increased hand trajectory standard deviation was evident at MID compared to BC ($F(1,37) = 8.09$, $p = 0.03$, $d = 0.95$) while similarly, **significantly** increased hand trajectory spanning sets were evident at MID compared to BC ($F(1,37) = 11.59$, $p < 0.01$, $d = 1.11$).

Paragraph Number 20 For the trajectory of the clubhead, females exhibited **significantly** increased standard deviation at TBS compared to MID ($F(1,37) = 16.82$, $p < 0.01$, $d = 0.61$) and at MID compared to BC ($F(1,37) = 21.01$, $p < 0.01$, $d = 1.35$). Similarly, females exhibited **significantly** increased clubhead trajectory spanning sets at TBS compared to MID ($F(1,37) = 6.32$, $p = 0.02$, $d = 0.47$) and at MID compared to BC ($F(1,37) = 15.39$, $p < 0.01$, $d = 0.78$). For the males, **significantly** increased clubhead trajectory standard deviation was evident at TBS compared to MID ($F(1,37) = 15.60$, $p < 0.01$, $d = 0.74$) and at MID compared to BC ($F(1,37) = 10.52$, $p < 0.01$, $d = 1.11$). **Significantly** increased clubhead trajectory spanning sets for males were also observed at TBS compared to MID ($F(1,37) = 17.84$, $p < 0.01$, $d = 0.81$) and at MID compared to BC ($F(1,37) = 10.20$, $p < 0.01$, $d = 0.87$).

DISCUSSION

Paragraph Number 21 The present study is the first to directly examine segment and inter-segment variability across phases of the downswing in male and female skilled golfers. The results indicate that although there are gender differences in movement variability for the thorax and pelvis, both genders achieve similar consistency in hand and clubhead trajectories in the final phases of the downswing. Supporting our hypotheses, skilled female golfers exhibited greater thorax and pelvis variability and greater variability in thorax-pelvis coupling than skilled male golfers.

Paragraph Number 22 Regardless of whether standard deviation or spanning set was employed as a measure of movement variability, similar results were obtained for the analysis of the male and female downswing. Gender differences were present in the latter half of the downswing, where females had greater axial rotation variability for the pelvis at MID and BC and the thorax at BC. The role that gender plays in rapid striking tasks has not been clearly established. In particular, how gender affects the control of accuracy dependent multi-joint tasks, or even if movement variability differences exist during functional tasks, is largely unknown. Greater absolute error and variable error has been observed for females when undertaking coincidence timing activities (open chain) (27, 37), and for lower limb segment axial rotation during cutting manoeuvres (closed chain) (22). Given that during treadmill walking joint variability has been reported to be lower in females than males (2), gender-related kinematic variability appears **to be** task dependent considering the higher levels of variability observed for females in this study. A goal directed task such as the golf swing imposes a task constraint on movement (14) and any differences, or similarities, in multi-segmental motion can reveal fundamental strategies required to strike the ball (16). Although variability differed between genders for the thorax and pelvis in the latter half of the downswing, variability was

the same for male and female hand and clubhead trajectories. Therefore, it is apparent that the dynamics of the arms play an important role in regulating the accuracy of the clubhead trajectory. Future research into control mechanisms of the golf swing will benefit from a focussed examination of arm segment motion, and the coordination between trunk and arm motion during the downswing.

Paragraph Number 23 Maximising end point accuracy in the final phases of a rapid movement task has been observed in other tasks such as when striking a stationary ball (32) and in reaching tasks involving single (26) and multiple joints (12). In agreement, our findings suggest that kinematic variability is also influenced by accuracy demands in the final phases of the downswing, although not necessarily by the initial phases of movement when generating power may be more of a priority. In regards to gender-specific strategies, thorax and pelvis axial rotation variability increased early in the female downswing before remaining consistent through to BC. In contrast, males remained consistent throughout the downswing except for lower thorax variability in the latter half of the downswing. Despite the motion of the thorax and pelvis both genders progressively decreased hand and clubhead trajectory variability throughout the downswing, once again supporting the notion that the arms play an important regulatory role in guiding the trajectory of the clubhead.

Paragraph Number 24 Thorax-pelvis coupling was consistent between swings for all movement directions, particularly in the latter half of the downswing. Interestingly, the variability of thorax-pelvis coupling was higher at TBS than MID and BC which is associated with the transitional movement pattern from the backswing to the downswing. That is, during the TBS phase of skilled golfers the pelvis begins rotating towards the target while the thorax is still rotating away; hence the segments are momentarily rotating in opposite directions (6, 23). Although never

formally examined, this is a voluntary movement strategy suggested to exploit a stretch-shorten type cycle in trunk muscles which assist in generating high upper body segment velocities early in the downswing (7, 23). As average coefficient of correspondence integrates both the magnitude and direction of angle-angle data over successive trials, segments rotating in opposite directions will result in lower average coefficient of correspondence (13, 35). Therefore, it should be noted that lower average coefficient of correspondence values at the TBS phase found in this study may not reflect decreased coordination, but rather the change in direction of segmental movement.

Paragraph Number 25 Similar to the results for thorax and pelvis axial rotation, the consistency of thorax-pelvis coupling for the female golfers was lower than for the male golfers in the latter half of the downswing for all directions of movement. Although gender differences in coupling variability were evident, the variability of end-point trajectories was similar between genders throughout the downswing phase. While it is important to maintain low levels of variability of the clubhead, males and females appeared to utilise different coordination strategies to achieve this. The origins of segment and inter-segment movement variability are not well understood, however it could be argued that the observed gender differences originate from the variability associated primarily with motor execution processes. The neuro-mechanical processes associated with goal directed movements, such as hitting a golf ball, can be divided into three stages; localization, planning and motor execution (34). Localization involves processing the location of the target and end-effector, while the movement planning stage involves the selection of motor commands that produce the intended movement. Although variability at any stage can ultimately affect the outcome, the task of hitting the golf ball was well defined and

fixed from trial-to-trial. Therefore the motor execution stage is most likely where differences in consistency arise during the downswing of skilled golfers.

Paragraph Number 26 Certain methodological issues should be considered in studies of movement variability. When measuring 3D kinematics via traditional marker based optoelectronic systems, variability of measurement can be increased when different testers apply markers and when measurements are made over different sessions (21). In the current study these potential sources of variability were minimised as a single examiner applied all markers, and swings from the same session were analysed without the reapplication of markers. Any variability in measurement was most likely a result of (i) the inherent motor variability associated with the task and (ii) the error associated with movement of markers on the skin. While skin marker movement error is difficult to eliminate, it is likely to be systematic and will in part be accounted for by the filtering process. The question of whether to use a standardised club for all golfers is also a point of interest. Detailed simulations using a shoulder-arm-club model have illustrated that manipulating properties of the club such as length, inertia, and shaft compliance will alter the torque required to drive the club (30). Therefore if the golfer is instructed to use a club that is not familiar to them, a swing pattern that is different to their natural swing may emerge. While we did not measure clubhead or shaft parameters, it is unlikely that gender-related differences in **golf swing kinematics** are solely the result of discrepancies of each individual's golf club. For example, changing selective club and shaft parameters such as increasing club length by up to 10 cm or altering shaft compliance, produces only modest increases in clubhead speed (1-2.5%) (30). It is more likely that differences in kinematic variability were due to intrinsic factors such as gender related differences in

anthropometrics, strength, and the associated differences in neuromuscular recruitment strategies required when performing the same task.

Paragraph number 27 The findings of this study can be extended in the future by exploring the causal relationship between neuromotor variability and the accuracy of striking the ball. It would be of considerable interest to coaches and clinicians to determine if pelvis and/or thorax segment motion, particularly in the latter part of the downswing has a substantial influence on the direction of ball travel or whether the arm segments are the main regulators of clubhead trajectory. Furthermore, the current study explicitly examined the kinematics of skilled golfers and the results should not be generalised beyond this. Examining how coordination differs among skill levels or golfers playing with injury, and how changes in these measures correspond to improving golf performance, would be of interest to coaches and clinicians alike.

CONCLUSION

Paragraph Number 28 **The present study revealed that gender differences exist for trunk movement variability, but not hand and clubhead trajectory variability during the downswing of skilled golfers.** The similar levels of hand and clubhead variability exhibited by males and females, regardless of the variability in the larger more proximal segments, suggests that the arms play a regulatory role in guiding the trajectory of the clubhead. It is apparent that the priority of skilled golfers is to progressively minimise hand and clubhead trajectory variability towards BC, despite the individual motion or coupling of the thorax and pelvis.

CONFLICT OF INTEREST

Paragraph Number 29 The authors declare that there are no conflicts of interest.

Paragraph Number 30 The results of the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES

1. Arutyunyan GH, Gurfinkel VS, Mirskii ML. Organisation of movements on execution by man of an exact postural task. *Biophys.* 1969;14:1162-1167.
2. Barrett R, Noordegraaf MV, Morrison S. Gender differences in the variability of lower extremity kinematics during treadmill locomotion. *J Mot Behav.* 2008;40(1):62-70.
3. Bartlett R, Wheat J, Robins M. Is movement variability important for sports biomechanists? *Sports Biomech.* 2007;6(2):224-243.
4. Bernstein N. *The coordination and regulation of movements.* Oxford: Pergamon; 1967. p. 1-196.
5. Bradshaw EJ, Keogh JW, Hume PA, Maulder PS, Nortje J, Marnewick M. The effect of biological movement variability on the performance of the golf swing in high- and low-handicapped players. *Res Q Exercise Sport.* 2009;80(2):185-196.
6. Burden AM, Grimshaw PN, Wallace ES. Hip and shoulder rotations during the golf swing of sub-10 handicap players. *J Sports Sci.* 1998;16(2):165-176.
7. Cheetham PJ, Martin PE, Mottram RE, St. Laurent BF. The importance of stretching the 'X-Factor' in the downswing of golf: 'The X-Factor stretch'. In: Thomas, PR. editors. *Optimising Performance in Golf.* Brisbane: Australian Academic Press, 2001, p. 192-199.

8. Cohen J. *Statistical power analysis for the behavioral sciences*. Hillsdale, NJ: Erlbaum; 1988. p. 8-14.
9. Cole MH, Grimshaw PN. The x-factor and its relationship to golfing performance. *J Quant Anal Sports*. 2009;5(1):1-19.
10. Giakas G, Baltzopoulos V. A comparison of automatic filtering techniques applied to biomechanical walking data. *J Biomech*. 1997;30(8):847-850.
11. Glazier PS, Davids K. The problem of measurement indeterminacy in complex neurobiological movement systems. *J Biomech*. 2009;42(16):2694-2696.
12. Gribble PL, Mullin LI, Cothros N, Mattar A. Role of cocontraction in arm movement accuracy. *J Neurophysiol*. 2003;89(5):2396-2405.
13. Heiderscheit BC, Hamill J, van Emmerik REA. Variability of stride characteristics and joint coordination among individuals with unilateral patellofemoral pain. *J Appl Biomech*. 2002;18(2):110-121.
14. Higgins S. Movement as an emergent form: Its structural limits. *Hum Movement Sci*. 1985;4(2):119-148.
15. Horan SA, Evans K, Morris NR, Kavanagh JJ. Thorax and pelvis kinematics during the downswing of male and female skilled golfers. *J Biomech*. 2010;43(8):1456-1462.
16. Knight CA. Neuromotor issues in the learning and control of golf skill. *Res Q Exercise Sport*. 2004;75(1):9-15.
17. Kurz MJ, Stergiou N. The spanning set indicates that variability during the stance period of running is affected by footwear. *Gait Posture*. 2003;17(2):132-135.
18. Kurz MJ, Stergiou N, Blanke D. Spanning set defines variability in locomotive patterns. *Med Biol Eng Comput*. 2003;41(2):211-214.

19. Latash ML, Levin MF. *Progress in Motor Control. Effects of Age, Disorder, and Rehabilitation*. Champaign, IL: Human Kinetics; 2004. p. 97-124.
20. Lay DC. *Linear algebra and its applications*. New York: Addison Wesley; 2002. p. 221-239.
21. McGinley JL, Baker R, Wolfe R, Morris ME. The reliability of three-dimensional kinematic gait measurements: A systematic review. *Gait Posture*. 2009;29(3):360-369.
22. McLean SG, Neal RJ, Myers PT, Walters MR. Knee joint kinematics during the sidestep cutting maneuver: potential for injury in women. *Med Sci Sports Exerc*. 1999;31(7):959-968.
23. Myers J, Lephart S, Tsai Y-S, Sell T, Smoliga J, Jolly J. The role of upper torso and pelvis rotation in driving performance during the golf swing. *J Sports Sci*. 2008;26(2):181-188.
24. Nesbit SM, McGinnis R. Kinematic analyses of the golf swing hub path and its role in golfer/club kinetic transfers. *J Sport Sci Med*. 2009;8(2):235-246.
25. Newell KM, Corcos DM. *Variability and motor control*. Champaign, IL: Human Kinetics; 1993. p. 1-12.
26. Osu R, Kamimura N, Iwasaki H, Nakano E, Harris CM, Wada Y, Kawato M. Optimal impedance control for task achievement in the presence of signal-dependent noise. *J Neurophysiol*. 2004;92(2):1199-1215.
27. Payne VG, Michael D. Effects of location of stimulus occlusion, stimulus velocity, and gender on coincidence-anticipation timing performance. *J Hum Movement Stud*. 1990;18:243-250.

28. Pollard CD, Heiderscheit BC, van Emmerik RE, Hamill J. Gender differences in lower extremity coupling variability during an unanticipated cutting maneuver. *J Appl Biomech.* 2005;21(2):143-152.
29. Sanders RH, Owens PC. Hub movement during the swing of elite and novice golfers. *Int J Biomech.* 1992;8(4):320-330.
30. Sharp R. On the mechanics of the golf swing. *Proc R Soc A.* 2009;465(2102):551-570.
31. Sigward SM, Powers CM. The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting. *Clin Biomech.* 2006;21(1):41-48.
32. Tabuchi N, Matsuo T, Hashizume K. Bat speed, trajectory, and timing for collegiate baseball batters hitting a stationary ball. *Sport Biomech.* 2007;6(1):17-30.
33. Tepavac D, Field-Fote EC. Vector coding: a technique for quantification of intersegmental coupling in multicyclic behaviors. *J Appl Biomech.* 2001;17:259-270.
34. van Beers RJ, Haggard P, Wolpert DM. The role of execution noise in movement variability. *J Neurophysiol.* 2004;91(2):1050-1063.
35. Wheat JS, Glazier P. Measuring coordination and variability in coordination. In: Davids, K, Bennett, S and Newell, K. editors. *Movement System Variability.* Champaign, IL: Human Kinetics, 2006, p. 167-181.
36. Williams KR, Sih BL. Changes in golf clubface orientation following impact with the ball. *Sports Eng.* 2002;5(2):65-80.
37. Wrisberg CA, Paul JH, Ragsdale MJ. Subject gender, knowledge of results and receptor anticipation. *Res Quart.* 1979;50:699-708.

38. Wu G, van der Helm FCT, Veeger HEJ, Makhsous M, Van Roy P, Anglin C, Nagels J, Karduna AR, McQuade K, Wang X, Werner FW, Buchholz B. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - part II: shoulder, elbow, wrist and hand. *J Biomech.* 2005;38(5):981-992.
39. Zheng N, Barrentine SW, Fleisig GS, Andrews JR. Kinematic analysis of swing in pro and amateur golfers. *Int J Sports Med.* 2008;29(6):487-493.
40. Zheng N, Barrentine SW, Fleisig GS, Andrews JR. Swing kinematics for male and female pro golfers. *Int J Sports Med.* 2008;29(12):965-970.

FIGURE CAPTIONS

Figure 1 Kinematic data were normalised to the downswing phase (0-100%) of the golf swing. Variability was examined at three discrete points (TBS, MID, BC) and three continuous phases (TBS \pm 20%, MID \pm 20%, and BC \pm 20%) associated with the downswing. Data from the three discrete points were used in the standard deviation analysis, whereas data from the three continuous phases were used in the spanning set and average coefficient of correspondence analyses.

Figure 2 Representative data for 3-D angular displacement for the thorax and pelvis segments from 5 trials, for a single male and a single female subject. Dotted vertical lines at 0% and 100% represent TBS and BC, respectively.

Figure 3 Standard deviations for 3-D angular displacement of the thorax and pelvis segments. Standard deviations were computed from five swings at three discrete data points (TBS, MID, and BC) for each individual. An ‘*’ indicates a significant

difference between genders, while ‘†’ and ‘‡’ indicate significant differences within the male and female downswings respectively. Error bars represent one standard error of the mean.

Figure 4 Spanning sets for 3-D angular displacement of the thorax and pelvis segments. Spanning sets were computed from five full swings at three continuous phases (TBS \pm 20%, MID \pm 20%, and BC \pm 20%) for each individual. An ‘*’ indicates a significant difference between genders, while ‘†’ and ‘‡’ indicate significant differences within the male and female downswings respectively. Error bars represent one standard error of the mean.

Figure 5 Representative angle-angle plots for thorax and pelvis data for a single female and male subject (left column). Average coefficient of correspondence was computed from angle-angle data, from the downswing of five swings for each subject (right column). Average coefficient of correspondence was calculated at three continuous phases (TBS \pm 20%, MID \pm 20%, and BC \pm 20%). An ‘*’ indicates a significant difference between genders, while ‘†’ and ‘‡’ indicate significant differences within the male and female downswings respectively. Error bars represent one standard error of the mean.

Figure 6 Standard deviations and spanning sets for hand and clubhead trajectory. Standard deviation was computed at the three discrete points (TBS, MID, and BC), while spanning set was computed at the three continuous phases (TBS \pm 20%, MID \pm 20%, and BC \pm 20%). An ‘*’ indicates a significant difference between genders, while ‘†’ and ‘‡’ indicate significant differences within the male and female downswings respectively. Error bars represent one standard error of the mean.

Figure1
[Click here to download high resolution image](#)

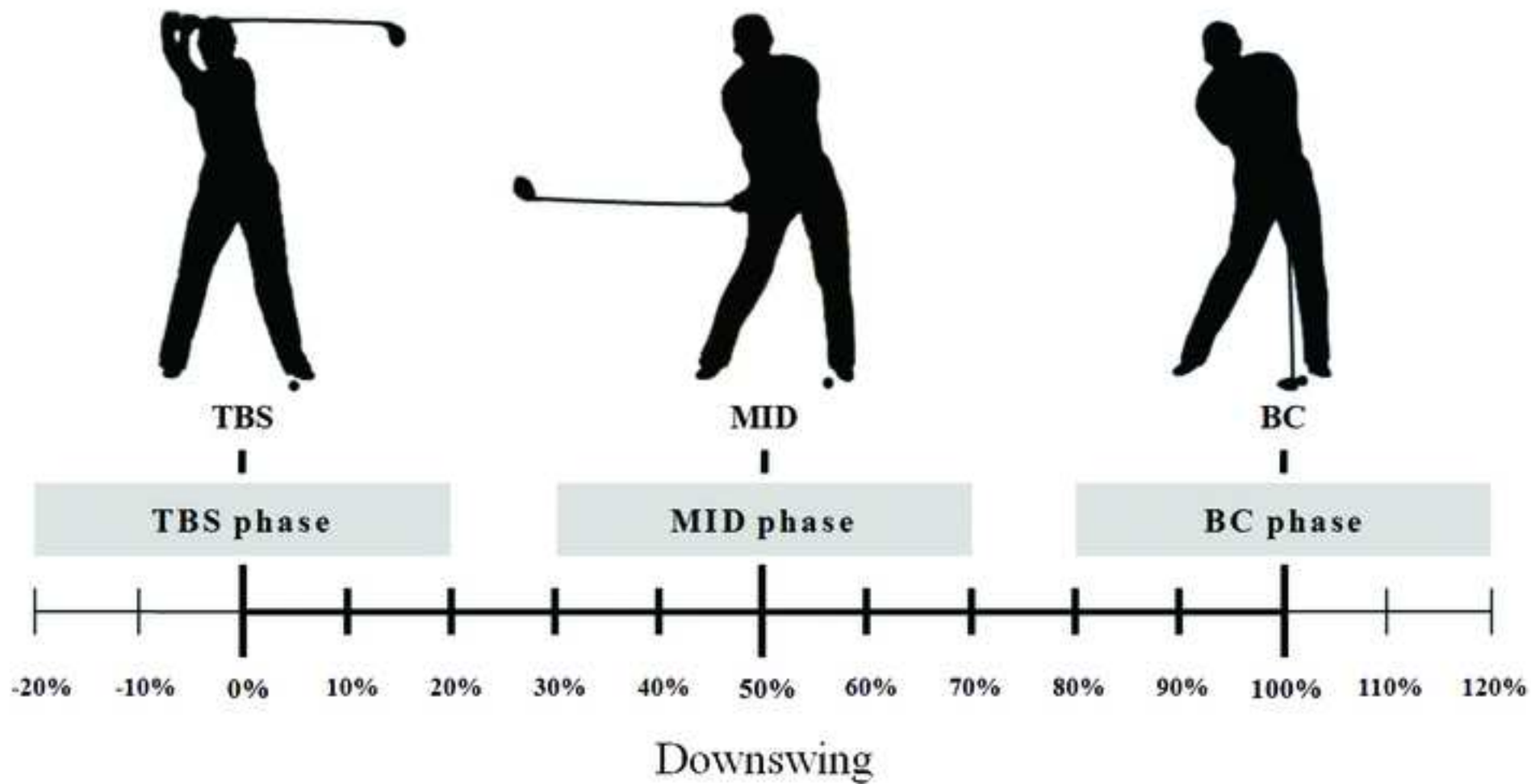


Figure2

[Click here to download high resolution image](#)

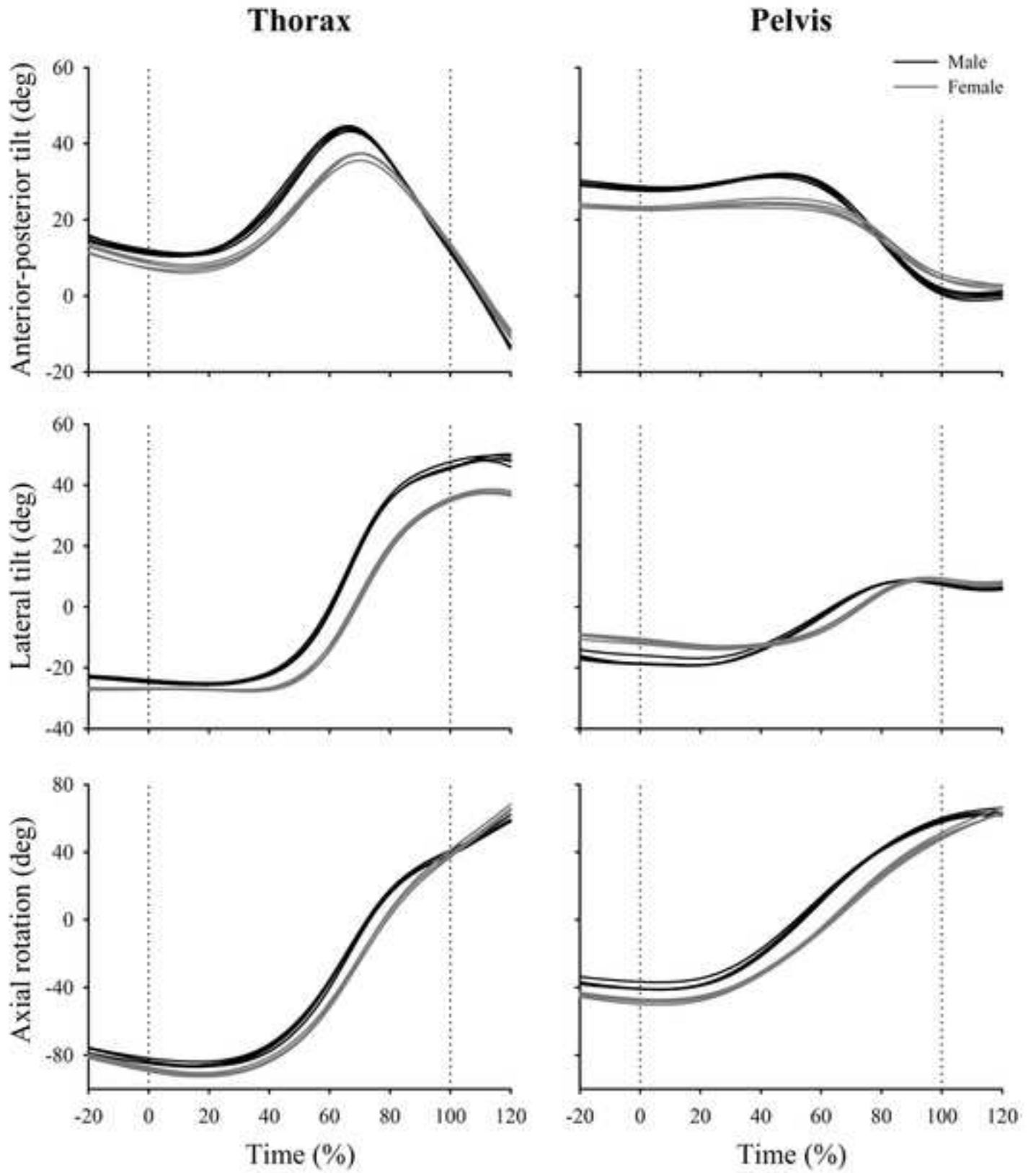


Figure3
[Click here to download high resolution image](#)

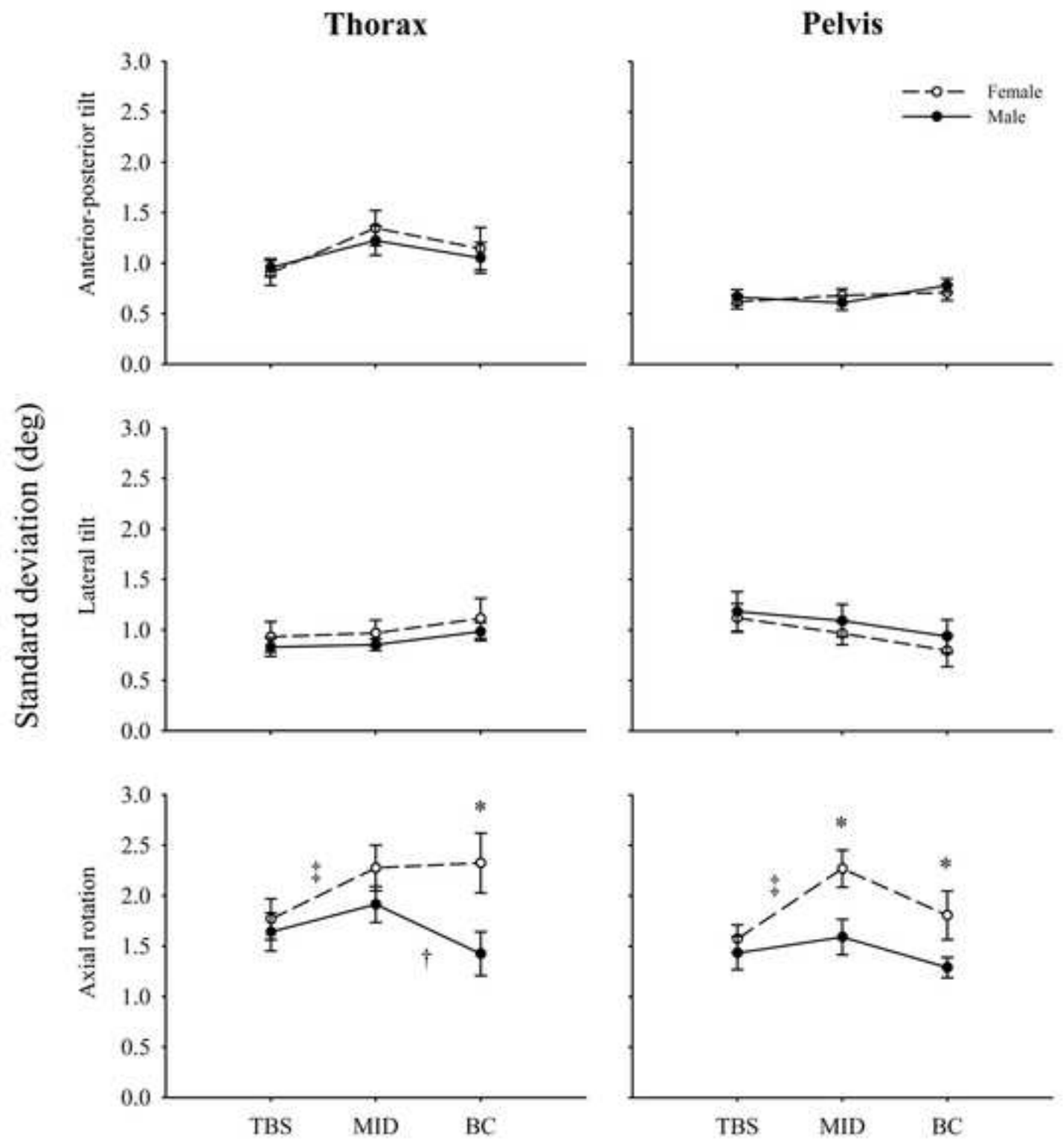


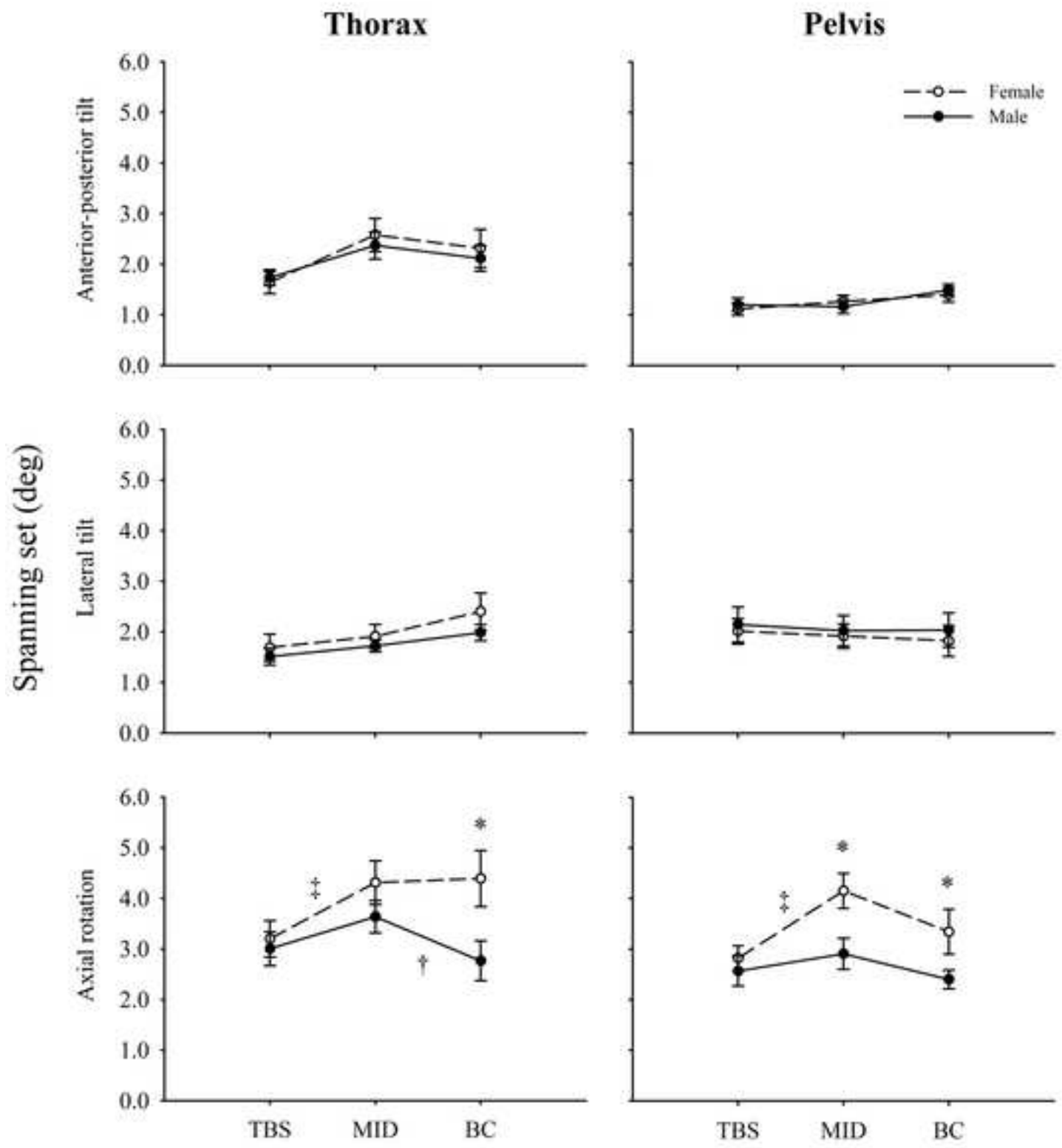
Figure4[Click here to download high resolution image](#)

Figure 5

[Click here to download high resolution image](#)

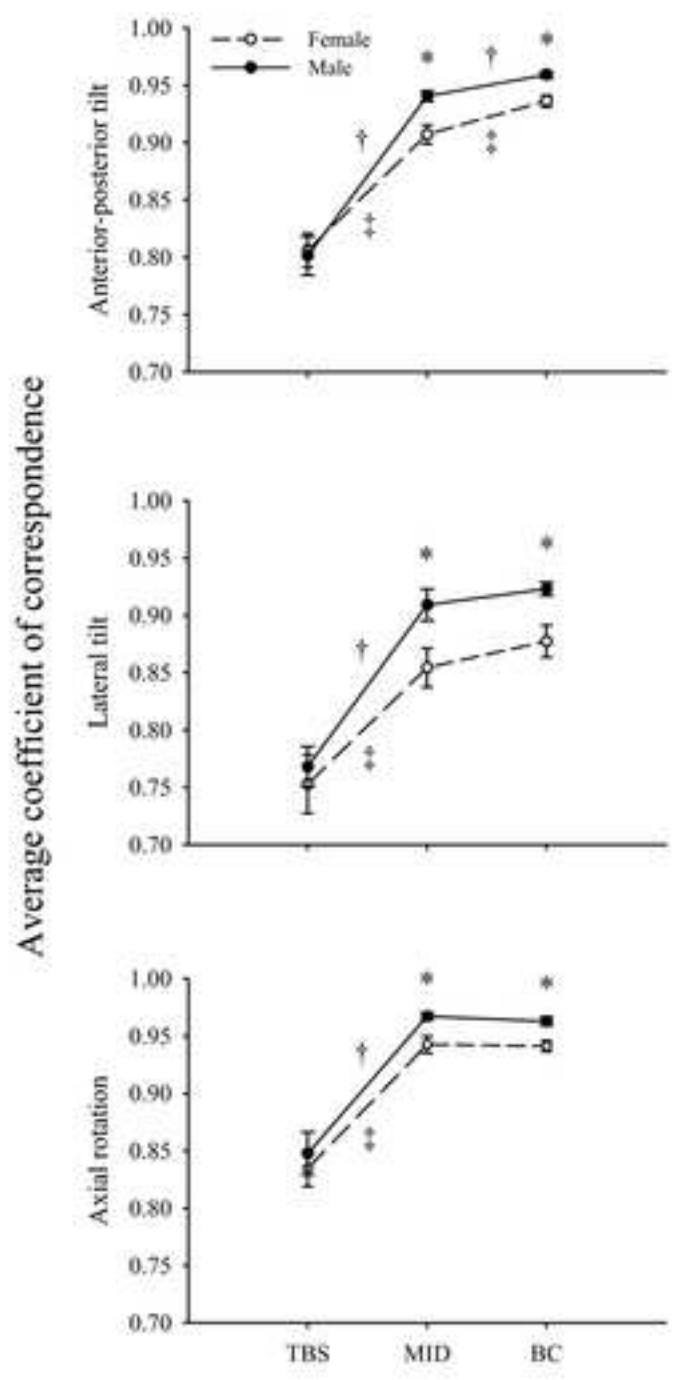
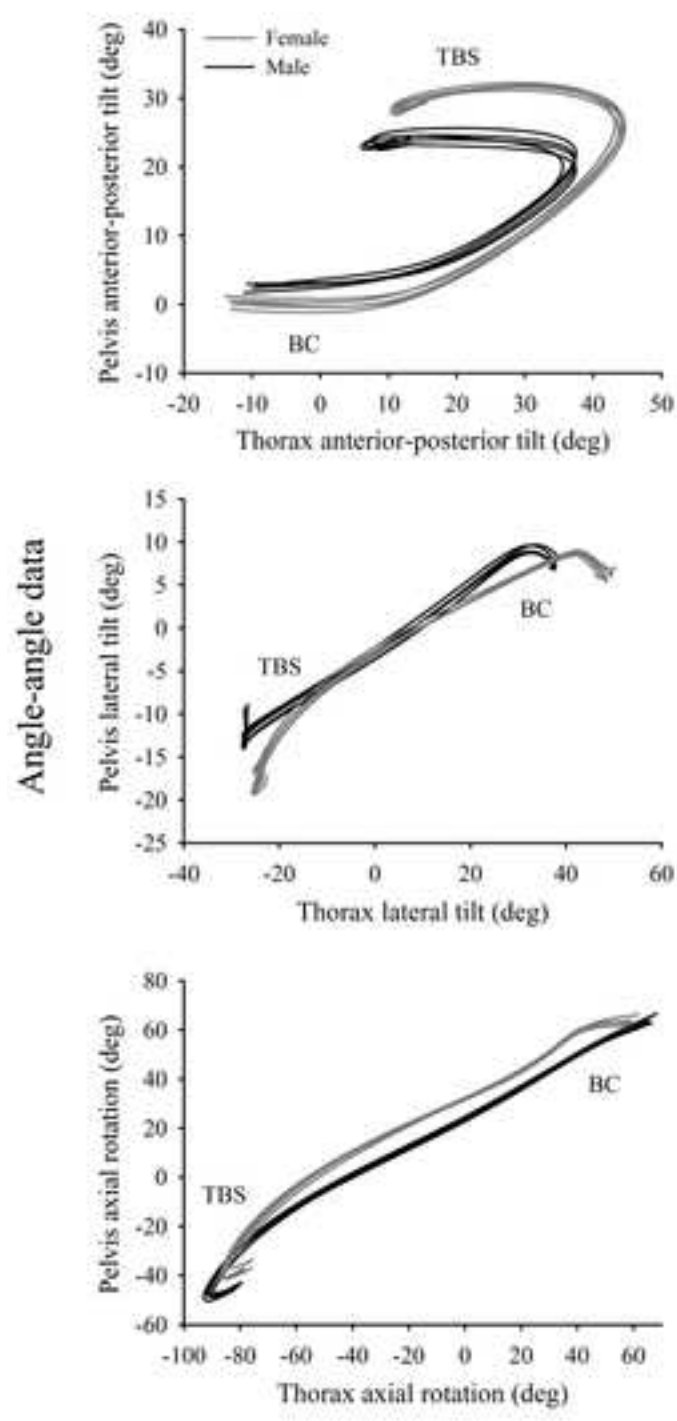


Figure6
[Click here to download high resolution image](#)

