Swing kinematics of male and female skilled golfers following prolonged putting practice

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Abstract

Given males and females respond differently to endurance based tasks, prolonged putting practice may provide an avenue to examine gender related differences in golf swing kinematics. The aim of this project was to determine if 40 minutes of putting affects thorax and pelvis kinematics during the full swing of males and females. Three-dimensional trunk kinematics were collected during the swings of 19 male (age: 26 ±7 years, hcp: 0.6 ±1.1) and 17 female (age: 24 ±7 years, hcp: 1.4 ±1.7) golfers before and after 40 minutes of putting. Angular displacement at address, top of backswing and ball contact for the pelvis, thorax, and pelvis-thorax interaction were calculated, in addition to the magnitude of peak angular velocity and repeatability of continuous segment angular velocities. Female golfers had less pelvis and thorax anterior-posterior tilt at address, less thorax and thorax-pelvis axial rotation at top of backswing, and less pelvis and thorax axial rotation and pelvis lateral tilt at ball contact pre- to post-putting. Analysis of peak angular velocities revealed females had significantly lower thorax-pelvis lateral tilt velocity pre- to post-putting. In conclusion, an endurance based putting intervention affects females' thorax and pelvis orientation angles and velocities to a greater extent than males.

Key words: Gender; Golf swing; Ecological validity; Endurance task.

1. Introduction

Investigations of the golf swing have typically examined upper body kinematics immediately following a simple warm up routine or brief familiarisation session. However, kinematic profiles observed immediately after a warm up may not reflect movement patterns following extended periods of activity, such as during a round, throughout a tournament, or even during a practice session. Several recent investigations have examined the effect of prolonged sport-specific tasks on the performance of multi-segment movements, and revealed that movement patterns can adapt over time to ensure that performance is maintained (Dierks, Manal, Hamill, & Davis, 2011; Holt, Bull, Cashman, & McGregor, 2003; Kellis, Katis, & Vrabas, 2006). Therefore, it is critical for the design of future golf studies, and the interpretation of previous studies, to determine if golf swing kinematics are altered following golf-specific interventions. Surprisingly, it is unknown if golf swing kinematics are altered following prolonged practice, or if prolonged practice affects males and females differently.

To ensure consistent and accurate swing patterns, skilled golfers spend a considerable amount of time practicing. Professional golfers will often hit in the order of 300 shots per session (Gosheger, Liem, Ludwig, Greshake, & Winkelmann, 2003; Theriault & Lachance, 1998), and make over 2000 swings per week (Jobe & Pink, 1996). This can equate to practice sessions in the order of 6-10 hours in duration (Theriault & Lachance, 1998). In addition to the full swing, skilled golfers spend a significant proportion of their time practicing putting (Lindsay & Horton, 2002). Putting and the full swing both require the golfer to maintain a relatively flexed trunk position. However, unlike the full swing the putting stroke involves minimal amounts of motion. The prolonged static postures adopted during putting practice significantly challenges the trunk and hip extensors (Evans, Refshauge, Adams, & Barrett, 2008), and leads to changes in posture and segmental orientation during the full golf swing (Evans et al., 2008; Watkins, Uppal, Perry, Pink, & Dinsay, 1996). It therefore stands to reason that if segmental orientation is affected by putting practice, so too will the ability to generate segmental velocity, which is arguably the most important performance measure of the full golf swing.

Current evidence suggests that males and females respond differently to endurance or fatiguing tasks (Hicks, Kent-Braun, & Ditor, 2001; Hunter, 2009), although this appears to be highly dependent on the requirements of the task. In general, females demonstrate greater endurance capacity than males during low to moderate intensity isometric type tasks (Clark, Collier, Manini, & Ploutz-Snyder, 2005; Hunter, 2009; Yoon, Schlinder Delap, Griffith, & Hunter, 2007), while differences are far less pronounced during higher intensity, dynamic movement tasks (Benjaminse, Habu, Sell, Abt, Fu et al., 2008; Hunter, 2009; Kernozek, Torry, & Iwasaki, 2008). From a motor control perspective, what may be more revealing than simply examining differences in endurance capacity during various tasks, could be to examine potential gender differences in the mechanics of functional activities following an endurance task. Such an approach was employed by Bonato and colleagues (2003), albeit in males only, where the effect of a repetitive endurance based task on lifting technique was examined. Results revealed that **participants** exhibited increases in both trunk range of motion as well as lumbar spine compressive forces during the lifting task (Bonato et al., 2003). In the context of the current study, few researchers have investigated the effect of a golf-specific endurance based task on full swing kinematics (Evans et al., 2008), particularly with male and female golfers. While prolonged putting is considered an endurance task that predominantly involves an isometric contraction of the trunk extensors, the physical requirements of the task are likely to be different for males and females and may influence the gender response.

The purpose of this study was to compare the effect of 40 minutes of putting practice on full swing kinematics in male and female skilled golfers. It was hypothesised that following the putting intervention, thorax and pelvis orientation angles would be affected differently in males and females, and similarly angular velocity would be affected differently in males and females. The results of this study will provide further insight into thorax and pelvis control strategies following a typical practice putting session, and assist in guiding appropriate practice habits and routines.

2. Methods

2.1 Participants

Nineteen male and 17 female skilled golfers volunteered to participate in the study. All **participants** were right-handed, free from pain or injury, and were either playing or trainee golf professionals or competitive amateur golfers (handicap ≤ 4). Written informed consent was obtained prior to data collection and all experimental procedures were approved by the relevant institution's Human Research Ethics Committee.

2.2 Experimental protocol

All data were collected in a laboratory setting. Upon arrival **participants** were interviewed to ascertain practice habits. Injury history and anthropometric measurements including height and mass were recorded. **Participants** then undertook a standardized 10 minute warm-up based on that of Fradkin et al. (2004), which included whole body movements and dynamic stretches of the major muscle groups involved in the golf swing, followed by hitting practice shots with a variety of clubs including their driver. The experimental setup consisted of hitting golf balls covered in retro-reflective tape from a rubber tee embedded in an artificial turf mat (1.8 × 1.8 m) into a net approximately 3 m away. All **participants** were instructed to address the ball in a neutral stance position, imagine they were on the tee, and hit their usual driver shot as straight as possible. Two vertical lines were placed on the net 0.5 m apart, and any shot not between the lines was deemed a mis-trial and another shot was performed. **Participants** hit five full driver swings using their own driver.

After five initial swings were collected, each golfer undertook a 40 minute putting intervention, which involved hitting putts along a mat to a hole from a range of self-selected distances (Evans et al., 2008). **Participants** were free to walk around the putting area, and were instructed not to sit or rest at any point during the 40 minute session. The intervention was intended to simulate a typical practice putting session, where **participants** experienced the same physical requirements and demands associated with putting practice at a course or driving range. To enhance intra-subject repeatability, all reflective markers used in the capture of 3-dimensional swing data remained attached to the subject during the putting task (Cappozzo, Della Croce, Leardini, & Chiari, 2005; McGinley, Baker, Wolfe, & Morris, 2009). Immediately following the completion of the putting task, **participants** performed another 5 full swings with their driver.

2.3 Kinematic data collection and modelling

Three-dimensional marker trajectories were collected at 500 Hz using a Vicon motion analysis system and modelled using BodyBuilder software version 3.6 (Oxford Metrics, Oxford, UK). Industry-specified standards indicate maximum absolute error rates in the order of 1mm for reconstruction of 3-dimensional marker displacements, and root-mean square error rates of 1.4 degrees for 3-dimensional angles. In the current study, reflective markers were attached to the pelvis on the right and left anterior-superior iliac spines and posterior-superior iliac spines. Additionally, markers were attached to the thorax over the suprasternal notch, xiphoid process, C7 and T10 spinous processes. A local coordinate system used for kinematic modelling was created, by attaching markers to the right and left heel of the subject’s golf shoes which approximated the calcanei (Horan, Evans, Morris, & Kavanagh, 2010; Horan & Kavanagh, 2012). Clubhead trajectory was tracked via a marker attached to the subject’s driver. Raw 3-dimensional coordinate data were filtered using a zero-lag fourth-order low-pass Butterworth filter. Marker cut-off frequencies for individual **participants** were between 6 and 10 Hz, as determined through residual analysis (Winter, 1990), with an r^2 threshold of 0.85.

Thorax and pelvis kinematics were calculated relative to a 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 oriented with the two heel markers and directed towards the target. 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*-axes. Modelling procedures for the thorax and pelvis were based on International Society of Biomechanics guidelines (Wu, Siegler, Allard, Kirtley, Leardini et al., 2002; Wu, van der Helm, Veeger, Makhsous, Van Roy et al., 2005). In addition to thorax and pelvis motion relative to a local coordinate system, the motion of the thorax relative to the pelvis (thorax-pelvis) was also calculated. Lateral tilt, anterior-posterior (a-p) tilt, and axial rotation were defined as angular rotation of the child segment about the parent segment *x*, *y,* and *z* axes respectively, using Euler angle calculations. Thorax, pelvis and thorax-pelvis angular velocities were determined at top of backswing, ball contact, and point of peak downswing velocity using the Poisson equation (Zatsiorsky, 1998), while peak clubhead and ball speed were calculated as the magnitude of the velocity vector determined from the clubhead marker and reflective golf ball, respectively.

2.4 Data analysis

All data analyses were performed using custom-designed software in Matlab version 7.8.0 (MathWorks, Natick, MA). In the present study kinematic data were examined at discrete points in the golf swing, as well as continuously during the downswing. For the discrete analysis, angular displacement at the time points of ball address, top of backswing and ball contact were calculated. Ball address was defined as the frame immediately prior to the club starting the backswing, top of backswing as the frame where the pelvis stops axially rotating away from the target and begins rotating towards the target and ball contact as the frame where the ball first starts to move. Additionally, the magnitude of peak angular velocity during the downswing phase was determined for the pelvis, thorax, and pelvis-thorax interactions.

For the continuous analysis, kinematic data were analyzed over the entire downswing phase of the swing, defined as the period from top of backswing to ball contact. Downswing data were normalised to 101 points for each individual using piecewise cubic spline interpolation. After normalisation, repeatability of continuous segment angular velocity data was quantified using the coefficient of multiple determination (Kadaba, Ramakrishnan, Wootten, Gainey, Gorton et al., 1989). The coefficient of multiple determination is a measure of waveform repeatability for which a value of 0 indicates no repeatability between waveforms, and 1 indicates perfect agreement between waveforms. To determine the effect of 40 minutes of putting on the consistency of velocity profiles, coefficient of multiple determinations were calculated for the 5 swings pre and 5 swings post putting task.

2.5 Statistical analysis

As gender differences exist in thorax and pelvis angular displacement and velocity at top of backswing and ball contact for male and female skilled golfers (Horan et al., 2010), change scores were calculated by taking the difference between pre- and post-intervention for each variable (thorax, pelvis and thorax-pelvis angular displacements and velocities) at ball address, top of backswing and ball contact. Positive change scores indicate an increase in angular displacement or velocity post putting intervention, while negative change scores indicate a decrease in angular displacement or velocity post putting intervention. One-way analysis of variance (SPSS for Windows 17.0, SPSS, Chicago, IL) was used to test for differences in change scores between males and females. Assumptions of normality were checked and confirmed by plotting the dependent variables using quantile-quantile plots in SPSS. Repeated measures analysis of variance with Tukey's honestly significant difference were used to test for differences between coefficient of multiple determinations for male and female participant's pre and post putting intervention. All results are presented as the mean ± one standard error of the mean unless otherwise stated. The level of significance was set at $p < 0.05$, and effect sizes were reported as Cohen's *d* (Cohen, 1988).

3. Results

3.1 Descriptive subject data

Male golfers were significantly taller and had greater body mass than females (Table 1). No gender differences were identified for handicap, golf playing experience or practice hours per week. No differences in clubhead or ball speed were identified pre- to post-intervention.

<<Insert Table 1>>

3.2 Thorax and pelvis angular displacement at discrete points in the golf swing

Females had significantly greater change scores at ball address, top of backswing and ball contact (Table 2). Specifically, female golfers had less pelvis and thorax a-p tilt at ball address, less thorax and thorax-pelvis axial rotation at top of backswing, and less pelvis and thorax axial rotation and pelvis lateral tilt at ball contact from pre- to post-putting conditions.

<<Insert Table 2>>

3.3 Thorax and pelvis angular velocity at discrete points in the downswing

Females had significantly greater change scores for peak thorax-pelvis lateral tilt velocity, where females had lower peak velocity from pre- to post-putting conditions (males: 10.0 ± 2.3 $deg.s^{-2}$, females: -5.3 ± 4.1 $deg.s^{-2}$, $F_{1,34} = 11.02$, $p = 0.002$, ES = 1.14). No gender differences were identified for any angular velocity measurement at top of backswing or ball contact.

3.4 Repeatability of thorax and pelvis angular velocity in the downswing

Overall coefficient of multiple determinations were high, with all values ranging from 0.902 to 0.991 across both genders and for both the pre-putting and post-putting conditions. For female golfers, coefficient of multiple determinations for thorax and thorax-pelvis axial rotation velocity significantly decreased following the putting intervention (Table 3). For male golfers, coefficient of multiple determinations for thorax-pelvis axial rotation velocity significantly decreased following the putting intervention.

<<Insert Table 3>>

4. Discussion

This study is the first to examine the effect of a practice putting intervention on upper body kinematics during the full golf swing of both male and female skilled golfers. Pelvis and thorax angular displacement was examined at discrete events during the golf swing to determine if upper body orientation was affected by the intervention. Given that coordinated motion of the pelvis and thorax is a key factor in generating clubhead speed (Cheetham, Martin, Mottram, & St. Laurent, 2001; Myers, Lephart, Tsai, Sell, Smoliga et al., 2008), it was also of interest to determine if changes in segment orientation were accompanied by changes in angular velocity. It was hypothesised that following the putting intervention differences in thorax and pelvis orientation angles would be most evident for females compared to males, and that thorax and pelvis angular velocity would be affected in females more than males.

A confirmed hypothesis of this study was that gender differences in thorax and pelvis orientation emerged following 40 minutes of putting. At ball address, females had a greater change in thorax and pelvis orientation than males, where a more upright posture was adopted by the females after the intervention. While there is no evidence that pelvis or thorax orientation at ball address has a causal effect on the dynamics of the downswing, it does indicate that the intervention affected address posture for females. An important finding that does relate to the downswing was that females had less magnitude of thorax and pelvis rotation at both top of backswing and ball contact following the intervention. Furthermore, the relative rotation between the two segments was also less in females at top of backswing and ball contact. Arguably, the coordination between segments is more reflective of functional performance than the motion of individual segments (Bartlett, Wheat, & Robins, 2007). Therefore, the altered coordination of thorax-pelvic rotation for females at top of backswing and ball contact could affect velocity characteristics throughout the downswing.

While gender-related orientation differences were most evident for axial rotation at top of backswing and ball contact, velocity differences were not observed at these downswing events. Instead, females had lower thorax-pelvis lateral tilt peak velocity following the intervention, suggesting that males and females are affected differently following 40 minutes of putting. It is possible that a degree of trunk extensor muscle fatigue was experienced by the golfers in the current study, as the current putting intervention has been shown to decrease extensor endurance time for the Biering-Sørensen test by 21% in elite male golfers (Evans et al., 2008). Fatigued trunk extensors can lead to impaired proprioceptive acuity (Taimela, Kankaanpää, & Luoto, 1999), altered muscle spindle activity (Ebaugh, McClure, & Karduna, 2006), an increase in the common drive to motor units (Contessa, Adam, & De Luca, 2009), and the number of motor units required to perform the task (Contessa et al., 2009). Such neuromuscular adaptations could lead to a reduced capacity to regulate trunk motion, particularly during a complex 3-dimensional movement such as the golf swing.

Interestingly, despite differences in peak velocity characteristics following the intervention, both groups were able to produce similar clubhead and ball velocities. A compensation strategy was most likely employed to achieve the goal of maintaining high clubhead speeds. Although not a feature of this study, it cannot be ruled out that the neuromuscular system altered the role that the arms play during the swing to ensure high clubhead speeds were maintained. Possible compensatory roles of the arms have been previously observed in skilled golfers, where low levels of hand and clubhead movement variability exist despite relatively high levels of thorax and pelvis movement variability (Horan, Evans, & Kavanagh, 2011). Prioritising movement control of the endpoint effector is a common observation in many goal directed tasks, and even when fatigued, displacement and velocity of endpoint effectors can remain invariant despite changes in proximal segment kinematics (Côté, Mathieu, Levin, & Feldman, 2002; Forestier & Nougier, 1998). Future work should involve specific examination of the arms and their role in generating high segment and clubhead velocity.

Coefficient of multiple determination analysis for segment velocities revealed several important findings which would not have been highlighted by examining peak velocities alone. While males and females demonstrated similarly high levels of repeatability for thorax and pelvis angular velocity over successive downswings, following the putting task both genders displayed decreased repeatability of thorax-pelvis axial rotation velocity. However, this reduced repeatability did not affect clubhead and ball velocity following the putting intervention. Decreased intra-subject repeatability of trunk velocity profiles without corresponding changes in clubhead velocity suggests that fluctuations in the velocity at the level of the trunk may be refined via segments distal to the thorax. Furthermore, different coordination strategies may be employed following the putting intervention where unfatigued muscles of the arms, or less fatigued muscles of the trunk are recruited to complete the goal-directed task (Côté et al., 2002; Gates & Dingwell, 2008). Madigan and colleagues (2006) investigated joint kinematic variability following a trunk extensor fatiguing task, and in line with the results of the current study found lower consistency of trunk and hip joint angular displacements and velocities, albeit for an upright standing task. Decreased consistency of kinematic profiles suggests that over multiple swings or trials, different motor control patterns emerge while the overall goal of the task is preserved (Forestier & Nougier, 1998).

The findings from this study have important implications for the design of future golf studies, and the interpretation of previously reported results. Currently, there is debate over whether the validity of laboratory based analyses reflect actual golf performance (Davids, Button, Araújo, Renshaw, & Hristovski, 2006; Evans, Horan, Neal, Barrett, & Mills, 2012). Instead, there may be just as much importance in considering the physiological status of the golfers at the time of swing assessment. We have shown that swing kinematics are different following a simple warm-up compared to a functional task that is reflective of what occurs in a true golf setting. Furthermore, given that the putting intervention had a greater influence on female kinematics, factors such as gender should be more closely considered in golf studies. Although males and females respond to fatiguing tasks differently (Hicks et al., 2001; Hunter, 2009; Hunter, Critchlow, Shin, & Enoka, 2004; Yoon et al., 2007), it is well recognised that the mechanisms of fatigue are specific to the requirements of the task (Hunter, 2009). Therefore the results of this study are relevant to the intervention prescribed. From a practical perspective, golfers and golf instructors should carefully consider the duration of training or instruction sessions, particularly when working with different genders. While more rigorous investigation is warranted, endurance training programs aimed at improving a golfers ability to manage static golf postures may also be of benefit to skilled golfers (Evans et al., 2008). The results from past or future golf studies conducted in tightly controlled settings not representative of real golfing environments should be generalised to field based settings with appropriate caution.

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Conflicts of interest statement

All authors declare no conflicts of interest.

References

Bartlett, R., Wheat, J., & Robins, M. (2007). Is movement variability important for sports biomechanists? *Sports Biomechanics, 6*, 224-243.

Benjaminse, A., Habu, A., Sell, T., Abt, J., Fu, F., Myers, J. et al. (2008). Fatigue alters lower extremity kinematics during a single-leg stop-jump task. *Knee Surgery, Sports Traumatology, Arthroscopy, 16*, 400-407.

Bonato, P., Ebenbichler, G. R., Roy, S. H., Lehr, S., Posch, M., Kollmitzer, J. et al. (2003). Muscle fatigue and fatigue-related biomechanical changes during a cyclic lifting task. *Spine, 28*, 1810-1820.

Cappozzo, A., Della Croce, U., Leardini, A., & Chiari, L. (2005). Human movement analysis using stereophotogrammetry. Part 1: Theoretical background. *Gait & Posture, 21*, 186-196.

Cheetham, P. J., Martin, P. E., Mottram, R. E., & St. Laurent, B. F. (2001). The importance of stretching the 'X-Factor' in the downswing of golf: 'The X-Factor stretch'. In P. R. Thomas (Ed.), *Optimising Performance in Golf* (pp. 192-199). Brisbane: Australian Academic Press.

Clark, B. C., Collier, S. R., Manini, T. M., & Ploutz-Snyder, L. L. (2005). Sex differences in muscle fatigability and activation patterns of the human quadriceps femoris. *European Journal of Applied Physiology, 94*, 196-206.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum.

Contessa, P., Adam, A., & De Luca, C. J. (2009). Motor unit control and force fluctuation during fatigue. *Journal of Applied Physiology, 107*, 235-243.

Côté, J., Mathieu, P., Levin, M., & Feldman, A. (2002). Movement reorganization to compensate for fatigue during sawing. *Experimental Brain Research, 146*, 394-398.

Davids, K., Button, C., Araújo, D., Renshaw, I., & Hristovski, R. (2006). Movement models from sports provide representative task constraints for studying adaptive behavior in human movement systems. *Adaptive Behavior, 14*, 73-95.

Dierks, T. A., Manal, K. T., Hamill, J., & Davis, I. (2011). Lower extremity kinematics in runners with patellofemoral pain during a prolonged run. *Medicine & Science in Sports & Exercise, 43*, 693-700.

Ebaugh, D. D., McClure, P. W., & Karduna, A. R. (2006). Effects of shoulder muscle fatigue caused by repetitive overhead activities on scapulothoracic and glenohumeral kinematics. *Journal of Electromyography & Kinesiology, 16*, 224-235.

Evans, K., Horan, S. A., Neal, R. J., Barrett, R. S., & Mills, P. M. (2012). Repeatability of three-dimensional thorax and pelvis kinematics in the golf swing measured using a field-based motion capture system. *Sports Biomechanics, 11*, 262-272

Evans, K., Refshauge, K., Adams, R., & Barrett, R. (2008). Swing kinematics in skilled male golfers following putting practice. *Journal of Orthopaedic & Sports Physical Therapy*, *38*, 425-433.

Forestier, N., & Nougier, V. (1998). The effects of muscular fatigue on the coordination of a multijoint movement in human. *Neuroscience Letters, 252*, 187-190.

Fradkin, A. J., Sherman, C. A., & Finch, C. F. (2004). Improving golf performance with a warm up conditioning programme. *British Journal of Sports Medicine, 38*, 762-765.

Gates, D., & Dingwell, J. (2008). The effects of neuromuscular fatigue on task performance during repetitive goal-directed movements. *Experimental Brain Research, 187*, 573-585.

Gosheger, G., Liem, D., Ludwig, K., Greshake, O., & Winkelmann, W. (2003). Injuries and overuse syndromes in golf. *The American Journal of Sports Medicine, 31*, 438-443.

Hicks, A. L., Kent-Braun, J., & Ditor, D. S. (2001). Sex differences in human skeletal muscle fatigue. *Exercise and Sport Sciences Reviews, 29*, 109-112.

Holt, P. J. E., Bull, A. M. J., Cashman, P. M. M., & McGregor, A. H. (2003). Kinematics of spinal motion during prolonged rowing. *International Journal of Sports Medicine, 24*, 597-602.

Horan, S. A., Evans, K., & Kavanagh, J. J. (2011). Movement variability in the golf swing of male and female skilled golfers. *Medicine & Science in Sports & Exercise, 43*, 1474-1483.

Horan, S. A., Evans, K., Morris, N. R., & Kavanagh, J. J. (2010). Thorax and pelvis kinematics during the downswing of male and female skilled golfers. *Journal of Biomechanics, 43*, 1456-1462.

Horan, S. A., & Kavanagh, J. J. (2012). The control of upper body segment speed and velocity during the golf swing. *Sports Biomechanics, 11*, 165-174.

Hunter, S. K. (2009). Sex differences and mechanisms of task-specific muscle fatigue. *Exercise and Sport Sciences Reviews, 37*, 113-122.

Hunter, S. K., Critchlow, A., Shin, I.-S., & Enoka, R. M. (2004). Fatigability of the elbow flexor muscles for a sustained submaximal contraction is similar in men and women matched for strength. *Journal of Applied Physiology, 96*, 195-202.

Jobe, F. W., & Pink, M. M. (1996). Shoulder pain in golf. *Clinics in Sports Medicine, 15*, 55-63.

Kadaba, M. P., Ramakrishnan, H. K., Wootten, M. E., Gainey, J., Gorton, G., & Cochran, G. V. (1989). Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *Journal of Orthopaedic Research, 7,* 849-860.

Kellis, E., Katis, A., & Vrabas, I. S. (2006). Effects of an intermittent exercise fatigue protocol on biomechanics of soccer kick performance. *Scandinavian Journal of Medicine & Science in Sports, 16,* 334-344.

Kernozek, T. W., Torry, M. R., & Iwasaki, M. (2008). Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. *The American Journal of Sports Medicine, 36,* 554-565.

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

Madigan, M. L., Davidson, B. S., & Nussbaum, M. A. (2006). Postural sway and joint kinematics during quiet standing are affected by lumbar extensor fatigue. *Human Movement Science, 25,* 788-799.

McGinley, J. L., Baker, R., Wolfe, R., & Morris, M. E. (2009). The reliability of three-dimensional kinematic gait measurements: A systematic review. *Gait & Posture, 29,* 360-369.

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

Taimela, S., Kankaanpää, M., & Luoto, S. (1999). The effect of lumbar fatigue on the ability to sense a change in lumbar position: A controlled study. *Spine, 24,* 1322.

Theriault, G., & Lachance, P. (1998). Golf injuries. An overview. *Sports Medicine, 26*, 43-57.

Watkins, R. G., Uppal, G. S., Perry, J., Pink, M., & Dinsay, J. M. (1996). Dynamic electromyographic analysis of trunk musculature in professional golfers. *American Journal of Sports Medicine, 24*, 535-538.

Winter, D. A. (1990). *Biomechanics and motor control of human movement* (2nd ed.). New York, NY: John Wiley & Sons, Inc.

Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D. et al. (2002). ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion - part I: ankle, hip, and spine. *Journal of Biomechanics, 35,* 543-548.

Wu, G., van der Helm, F. C. T., Veeger, H. E. J., Makhsous, M., Van Roy, P., Anglin, C. et al. (2005). 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. *Journal of Biomechanics, 38*, 981-992.

Yoon, T., Schlinder Delap, B., Griffith, E. E., & Hunter, S. K. (2007). Mechanisms of fatigue differ after low- and high-force fatiguing contractions in men and women. *Muscle & Nerve, 36*, 515-524.

Zatsiorsky, V. M. (1998). *Kinematics of human motion*. Champaign, IL: Human Kinetics.

Tables

Table 1. Descriptive data for all **participants** (mean ± standard deviation)

	Males (n=19)	**Females (n=17)**
Age (yrs)	26 ± 7	24 ± 7
Body mass (kg)	80.2 ± 9.1	61.9 ± 10.1*
Height (m)	1.80 ± 0.05	1.67 ± 0.06*
Handicap (strokes)	0.6 ± 1.1	1.4 ± 1.7
Playing experience (yrs)	12 ± 7	11 ± 7
Practice per week (hrs)	14 ± 8	17 ± 12

* Indicates significant gender difference at $p < 0.05$ level

Table 2. Change scores for angular displacement variables following 40 mins of putting

	Angle (deg)	**Males**	**Females**	***F*-statistic**	***p* value**	**ES**
ADD	Pelvis a-p tilt	-0.2 ± 0.2	-1.3 ± 0.2	$F_{1,34} = 7.20$	0.010	0.92
	Thorax a-p tilt	-0.3 ± 0.1	-1.6 ± 0.2	$F_{1,34} = 29.71$	< 0.001	1.88
TBS	Thorax axial rotation	-0.1 ± 0.4	-4.1 ± 0.5	$F_{1,34} = 41.42$	< 0.001	2.24
	Thorax-pelvis rotation	0.1 ± 0.3	-2.9 ± 0.5	$F_{1,34} = 19.08$	< 0.001	1.51
BC	Pelvis lateral tilt	0.3 ± 0.2	-0.6 ± 0.3	$F_{1,34} = 5.25$	0.020	0.78
	Pelvis axial rotation	-0.1 ± 0.3	-2.4 ± 0.5	$F_{1,34} = 14.98$	< 0.001	1.34
	Thorax axial rotation	-0.2 ± 0.3	-2.2 ± 0.5	$F_{1,34} = 10.72$	0.002	1.13

ADD = ball address; TBS = top of back swing; BC = ball contact; ES = effect size (Cohen's *d*)

Table 3. CMDs calculated from continuous velocity data pre and post 40 mins of putting

	Gender	**Pre**	**Post**	**Mean difference (95% CI)**	***p* value**	**ES**
Thorax axial rotation	F	0.989 ± 0.002	0.968 ± 0.008	0.021 (0.004 to 0.038)	0.015	1.71
Thorax-pelvis rotation	F	0.962 ± 0.017	0.936 ± 0.022	0.026 (0.004 to 0.048)	0.023	1.53
Thorax-pelvis rotation	M	0.940 ± 0.016	0.912 ± 0.020	0.028 (0.007 to 0.049)	0.010	0.60

CMD = coefficient of multiple determination