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Effects of fatigue on golf performance

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Abstract
The purpose of this study was to determine if body position, weight transfer, and/or pelvis/trunk rotations changed as a result of a golf specific fatiguing protocol and whether these changes affected resultant club head velocity at impact and shot consistency. Six male golfers and one female golfer participated in the study, who had a mean age, height, and body mass of 23.9 ± 3.9 years, 177.4 ± 4.9 cm, and 75.3 ± 9.9 kg, respectively. Path analysis was used to determine the relationships between fatigue, biomechanical variables, and resultant club head velocity at impact and shot consistency. In the statistical models representing the effects of biomechanical variables calculated at the top of the swing and ball contact, golf specific fatigue was associated with a 2.0% and 2.5% reduction in the club head velocity and a 7.1% and 9.4% improvement in the shot consistency, respectively. These data suggest that golf specific fatigue was not related to the initial lower body sagittal plane angles at address nor was simulated golf specific fatigue related to peak transverse plane pelvis and trunk rotational velocities (or their timings) in a manner that indicates a relationship to resultant club head velocity and shot consistency.

Keywords: Club head velocity, body position, weight transfer, rotation, path analysis

Introduction
To determine which techniques of the golf swing are most important to performance, it is common to refer to the mechanics of low-handicap golfers as a template for appropriate swing motion (Barrentine et al., 1994; McLaughlin & Best, 1994; McTeigue, 1994; Burden et al., 1998). Research in this area has led to a better understanding of some of the key characteristics of the address, backswing, downswing, and follow-through phases of the golf swing. However, to our knowledge there has been no published study of the effect of fatigue from golf play on full swing variables associated with performance. In an actual round of golf, a player may take over 10,000 steps (Kobriger et al., 2006) and swing the club 100 times or more. To more fully address this question, it is not only important to determine which aspects of the golf swing change over time but also whether these changes are related to changes in the performance variables.
Golf performance is typically quantified by a player’s handicap or by their score on a particular course. However, other measures of performance must be substituted as surrogates when studying golf swing mechanics in a laboratory setting. In the case of the tee shot, the ability to generate long drives in a controlled and consistent manner is critical to the performance. Two variables that capture this information are resultant club head velocity (CHV) and shot trajectory consistency. The importance of CHV is supported by Fradkin et al. (2004) who previously determined that CHV was highly correlated with handicap, as low-handicap golfers tended to have higher CHV than high-handicap golfers. The importance of initial ball trajectory can be illustrated with a simple numerical example; a 1° change in ball trajectory on a straight-line 300 yard (274 m) drive may change the position of the ball by more than 5 yards (4.6 m) to the left or right.

Because of the relationship between CHV and performance, a great deal of research on swing mechanics has used CHV as the primary outcome measure. This type of research typically focuses on one or more of the following categories of variables to explain changes in CHV: body position (Egret et al., 2006), weight transfer (Barrentine et al., 1994; Ball & Best, 2007a, 2007b), and timing of rotations (Milburn, 1982; Burden et al., 1998). However, these studies tend to be descriptive in nature and do not provide information specifically indicating how these variables may affect performance; but rather they illustrate differences in performance between groups.

One way to investigate how these variables are related to performance over time is through the statistical method of path analysis (Kline, 2011). Path analysis provides a framework for treating the separate aspects of a golf swing as a coherent system that allows identification of the key characteristics that change during extended play and the relationship of these changes on markers of performance such as CHV. Specifically, path analysis allows for explicit linking of measured variables in a sequential manner (e.g. the order of body movement during a golf swing) using tools similar to those associated with linear regression. The primary difference between path analysis and regression is that the former allows modeling of systems of equations rather than a single equation.

While logic and colloquial opinion purport that full golf swing performance declines with fatigue, no research has formally examined the influence of fatigue on variables associated with golf performance. Therefore, the purpose of this study was to determine the relationships between simulated golf specific fatigue (SGSF), biomechanical variables, and performance variables related to the golf swing. Specifically, path analysis was used to determine if measures of body position, weight transfer, and pelvis and trunk rotational velocities changed over time and whether they affected two full swing performance variables: CHV and shot consistency.

**Methods**

**Participants**

Six male golfers and one female golfer, with a mean age, height, and body mass of 23.9 ± 3.9 years, 177.4 ± 4.9 cm, and 75.3 ± 9.9 kg, respectively, participated in the study. The participants were healthy recreational golfers averaging between 80 and 95 strokes (self-reported) while playing 18 holes of walked golf. The protocol was approved by the University’s Institutional Review Board and informed consent was obtained from each participant before data collection.

**Protocol**

The protocol was designed to simulate playing 18 holes of walked golf. The participants first warmed up by taking no more than 20 practice swings and stretching in the same manner as
they would before a round of golf using self-selected techniques. Then, they performed 20 full swing tee shots. Participants were instructed to hit the ball for maximum distance while maintaining accuracy on every shot. To simulate carrying a golf bag while walking, immediately following the 20 driver swings the participants walked one mile on a treadmill with no incline at a speed of 3.5 mph carrying a 20 pound backpack. This sequence of 20 swings and one-mile walk was repeated seven times.

A 10-camera Vicon MX motion capture system (Vicon, Lake Forest, CA, USA) was used to record three-dimensional (3-D) kinematics at 480 Hz for every swing during the protocol. Spherical reflective markers were adhered to the skin on 39 anatomical landmarks according to the Vicon Plug-in-Gait protocol (Vicon, Lake Forest, CA, USA) using double-sided tape. Spherical markers were also adhered to the club in four locations including the base of the grip, halfway down the club, the hosel of the club, and the club head. The club markers were used to determine events and the CHV during the swing. The golf ball was also wrapped in reflective tape so that ball flight information could be collected. Golfers wore tennis shoes, shorts, and tight fitting shirts to ensure accurate collection of 3-D data. Subject anthropometrics (height, weight, leg length, knee width, ankle width, shoulder offset, elbow width, wrist width, and hand thickness) were recorded before testing for input into the Plug-in-Gait model.

The golfers performed tee shots off of a golf mat placed on top of two force plates (one foot over each plate). Kinetic data were captured using two AMTI (Watertown, MA, USA) force plates at 1200 Hz. Tee height and tee position were determined by subject preference during the warm-up period and remained constant throughout the duration of the protocol. The golf mat was taped to the floor using carpet tape to ensure that the mat did not slide. Tee shots were directed onto a 3.05 m × 3.05 m × 3.05 m caged golf net.

**Data analysis**

The marker data were digitized using Vicon Workstation version 5.2.7 (Vicon, Lake Forest, CA, USA). The club markers and ball markers were filtered using a Woltring filter with a predicted mean square error value of 20. Events in the golf swing were defined as address, top of swing, and ball contact. Address was defined as the frame of data before the club head started into the backswing. The top of the swing was defined as the frame of data where the club stopped the backswing and began the downswing. Ball contact was defined as the frame of data where the club contacted the ball.

The sagittal plane lead leg ankle, knee and hip angles were calculated at address (LAKAD, LKNAD, and LHPAD), top of the swing (LAKTS, LKNTS, and LHPTS), and at ball contact (LAKBC, LKNBC, and LHPBC). The vertical ground reaction force was used to determine the percent of weight on the lead leg at the top of the swing (LTPTS) and at ball contact (LTPBC). CHV was also calculated at ball contact.

A custom written MATLAB (MathWorks, Boston, MA, USA) program was used to calculate the pelvis and thorax peak transverse plane angular velocity (PPLVV and PTHXV) and the timing of the thorax and pelvis peak transverse plane angular velocity with respect to ball contact (TPPLV and TPTHV). The timings (how long before or after ball contact) of the peak thorax and peak pelvis velocities were calculated in seconds, where a negative time indicated that the peak thorax or pelvis velocity occurred after ball contact.

Shot consistency for an individual swing was defined as the resultant distance between the ball position for that swing from the mean ball position for the entire set of swings. Ball position was determined for each shot at 0.5 m from the tee in the global XZ-plane, which was perpendicular to the direction the ball was hit. The mean ball position in the XZ-plane...
was calculated for each set of swings throughout the protocol. A lower value for this measure indicated greater shot consistency (smaller deviations from the mean) for that particular set of swings. Even numbered swings were processed for analysis.

Statistical analysis

Data were analyzed using path analysis with statistical software MPlus 5.0 (Muthen & Muthen, 2008) to determine whether there were significant relationships among the number of swings (time), the biomechanical variables of interest, and golf performance as measured by CHV and consistency. Specifically, a multilevel path analysis was used to test the models depicted in Figure 1. Data were organized into three groups: time, biomechanical variables, and outcome variables. The proxy for golf specific fatigue was the number of swings taken by the subjects. The biomechanical variables were defined as flexion/extension angles at the ankle, knee, and hip and vertical ground reaction forces at all three events, and peak pelvis and thorax transverse plane angular velocities and timing of these velocities. The outcome variables were defined as CHV and shot consistency. The significance of individual paths between the variables were tested using the $t$-statistic, with $\alpha = 0.05$. Interpretation of the relationships were made by examining the path coefficients linking variables, and depicted with the lines in the aforementioned figures with directions assigned by logical inference. Path coefficients are interpreted like correlation coefficients, wherein positive values for these

![Path Models](attachment:image)

Figure 1. Proposed path models: (a) address where LAKAD = lead ankle sagittal angle, LKNAD = lead knee sagittal angle, LHPAD = lead hip sagittal angle; (b) top of the swing where LTPTS = the percent of weight on the lead leg, LAKTS = lead ankle sagittal angle, LKNTS = lead knee sagittal angle, LHPTS = lead hip sagittal angle; (c) ball contact where LTPBC = the percent of weight on the lead leg, LAKBC = lead ankle sagittal angle, LKNBC = lead knee sagittal angle, LHPBC = lead hip sagittal angle; and (d) timing and angular velocities where PPLVV = peak pelvis angular velocity, PTHXV = peak thorax velocity, TPPLV = time to peak pelvis velocity, TPTHV = time to peak thorax velocity. For all models: time = number of swings; CHV = club head velocity at ball contact; consistency = the shot consistency.
coefficients indicated a relationship in which as one variable increased in value so did the other. On the other hand, a negative coefficient value indicated that as one variable increased in value, the other decreased. Because multiple data points (multiple swings) were collected for each subject, a multilevel analysis was conducted to account for within subject variation.

Results

While all of the biomechanical variables except LAKAD, LTPS, PTHXV, and TPPLV were associated with one or both of the performance variables, only LAKTS, LKNTS, and LTPBC were influenced by the SGSF protocol, Figure 2.

Specifically, SGSF was inversely related to LAKTS and LTPBC while it was directly related to LKNTS. These relationships were found at the top of the swing and at ball contact. To determine the indirect effects of the SGSF protocol on the dependent variables, the path coefficients along each path linking time to the dependent variables are multiplied and the resulting product represents the unit change in the dependent variable per unit change of the SGSF protocol.

To provide a context for the meaningfulness of these relationships, path coefficients were used to calculate the percent change in the CHV and shot consistency across the entire fatiguing protocol relative to the mean of pre-fatigue values of CHV (39.44 m/s) and shot consistency (0.11 m).

![Path model results](image)

Figure 2. Path model results: (a) address where LAKAD = lead ankle sagittal angle, LKNAD = lead knee sagittal angle, LHPAD = lead hip sagittal angle; (b) top of the swing where LTPS = the percent of weight on the lead leg, LAKTS = lead ankle sagittal angle, LKNTS = lead knee sagittal angle, LHPTS = lead hip sagittal angle; (c) ball contact where LTPBC = the percent of weight on the lead leg, LAKBC = lead ankle sagittal angle, LKNBC = lead knee sagittal angle, LHPBC = lead hip sagittal angle; (d) timing and angular velocities where PPLVV = peak pelvis angular velocity, PTHXV = peak thorax velocity, TPPLV = time to peak pelvis velocity, TPTHV = time to peak thorax velocity. For all models: time = number of swings; CHV = club head velocity at ball contact; consistency = the shot consistency.
In the statistical model representing the effects of biomechanical variables calculated at the top of the swing (Figure 2b), SGSF was associated with a 2.0% reduction in CHV and a 7.1% improvement in shot consistency. In the statistical model representing the effects of biomechanical variables calculated at ball contact (Figure 2c), SGSF was associated with a 2.5% reduction in CHV and a 9.4% improvement in shot consistency.

Discussion and implications

The purpose of this study was to use a multilevel path analysis to determine if significant relationships existed between SGSF, biomechanical variables, and swing performance variables. Path analysis provides a novel framework for investigating relationships between biomechanical and performance variables over time, allowing the analysis of a system of equations relating variables to one another. Also, because individual golfers were measured at multiple occasions, a multilevel modeling strategy was used in which subject served as a variable in the analysis, allowing the accounting of variance due to individual performance.

The only paths that linked the SGSF protocol to the biomechanical variables and ultimately the swing performance variables occurred at the top of the swing and at ball contact. These data suggest that SGSF was not related to the initial lower body sagittal plane angles at address nor was SGSF related to peak transverse plane pelvis and trunk rotational velocities (or their timings) in a manner that indicates a relationship to CHV and shot consistency.

Although SFSG was related to changes in CHV and shot consistency, the magnitudes of these relationships were different. Specifically, the relationship between SFSG and CHV was modest at best. While there were statistically significant paths linking SFSG to CHV at the top of the swing and ball contact, these paths were associated with 2% and 2.5% changes in CHV, respectively. On the other hand, the relationship between SFSG and shot consistency was more pronounced. Statistically significant paths linking SFSG and shot consistency at the top of the swing and ball contact were associated with approximately 7% and 9% changes in shot consistency, respectively. However, these changes were in the direction of improved shot consistency (less variation in ball trajectory), which was unexpected. The current data set does not provide any clear explanation for this phenomenon. Perhaps, golfers became more comfortable with the laboratory environment or protocol; large number of swings essentially functioned as a form of warm-up or familiarization process.

While variation in golf swing performance was not the focus of this study, it may provide some insight to our results. Bradshaw et al. (2009) examined the movement variability of skilled and unskilled golfers and its relationship to golf swing performance. They reported that one of the events in the golf swing where invariance was beneficial to performance was the top of swing. Knight (2004) has suggested that the only event (or phase) in the golf swing where invariance is critical to success is ball contact. Again, while not statistically examined in this study, if the SFSG protocol resulted in more variability in swing mechanics this may be why we observed significant relationship paths between SFSG and CHV and shot consistency at the top of the swing and at ball contact.

It is important to consider the limitations of this study when interpreting these results. First, simulating golf indoors in a lab environment does not account for variables found on the golf course such as temperature, changes in hitting surfaces, and the pressure to perform. Second, the number of swings taken (140) would normally be achieved only if the recreational caliber golfer took a practice swing before the majority of his/her shots. Third, club selection was fixed in the current study; all shots were taken with the driver. Fourth, the mileage walked while playing 18 holes of golf can vary greatly depending on the course
played. Fifth, while the golf tee was in the same position for all trials no specific control of foot position relative to the tee was enforced, therefore some variation in the golfers’ setup may have been present. Finally, the relatively small number of subjects used in the study may limit its generalizability.

Conclusion

The current study adds to the previous golf biomechanics literature by examining relationships among the variables by treating them as a coherent ordered system, rather than by examining the relationships in isolation. The results of this study provide some insight regarding the effects of SGSF on full golf swing performance variables. These results suggest that a majority of the biomechanical variables examined in this study are associated to some degree with changes in CHV and shot consistency. However, a relatively small number of significant relationships were found between SFSG and the intermediate biomechanical examined in this study. Since the biomechanical variables examined in this study are by no means exhaustive, future research could use the same methodological approach to investigate whether these results are due to a lack of influence of fatigue on swing performance or if fatigue affects other biomechanical aspects of the golf swing not examined in the current study.

References


