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Kinematic, Kinetic, and Temporal Metrics Associated With Golf Proficiency

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Abstract

McHugh, MP, O'Mahoney, CA, Orishimo, KF, Kremenic, IJ, and Nicholas, SJ. Kinematic, kinetic, and temporal metrics associated with golf proficiency. *J Strength Cond Res* XX(X): 000–000, 2023—The biomechanics of the golf swing have been studied extensively, but the literature is unclear on which metrics are indicative of proficiency. The purpose of this study was to determine which metrics identified golf proficiency. It was hypothesized that discrete kinematic, kinetic, and temporal metrics would vary depending on proficiency and that combinations of metrics from each category would explain specific proficiency metrics. Kinematic, kinetic, and temporal metrics and their sequencing were collected for shots performed with a driver in 33 male golfers categorized as proficient, average, or unskilled (based on a combination of handicap, ball velocity, and driving distance). Kinematic data were collected with high-speed motion analysis, and ground reaction forces (GRF) were collected from dual force plates. Proficient golfers had greater x-factor at ball impact and greater trunk deceleration before ball impact compared with average ($p < 0.05$) and unskilled ($p < 0.01$) golfers. Unskilled golfers had lower x-factor at the top of the back swing and lower peak x-factor, and they took longer to reach peak trunk velocity and peak lead foot GRF compared with average ($p < 0.05$) and proficient ($p < 0.05$) golfers. A combination of 2 kinematic metrics (x-factor at ball impact and peak pelvis velocity), 1 kinetic metric (peak lead foot GRF), and 2 timing metrics (the timing of peak trunk and arm velocity) explained 85% of the variability in ball velocity. The finding that x-factor at ball impact and trunk deceleration identified golf proficiency points to the potential for axial trunk rotation training to improve performance.

Key Words: biomechanics, x-factor, kinematic sequence, ground reaction force

Introduction

The biomechanics of the golf swing has been studied extensively, but the literature is unclear on which metrics are indicative of proficiency. The relationships between biomechanics and proficiency have been examined by comparing kinetic, kinematic, and temporal metrics between the groups stratified by differing playing proficiency (2,18,19,21,23) or by examining the associations between biomechanics metrics and proficiency metrics in players with homogeneous (6,9,10,13) and heterogenous (3,16,17) golf proficiency. Most studies have quantified proficiency using a player's official golf handicap index (2,13,19,21,23) or clubhead speed (6,9,10,16,17), whereas other studies have used ball velocity (3,18) as the index of proficiency. Some studies only examined kinematic metrics (9,10,13,18), and others only examined kinetic metrics (6,16). However, several studies examined kinematic and kinetic metrics associated with proficiency (3,17,19). One study examined kinematic and temporal metrics but did not examine kinetic metrics (23). An additional study examined kinetic and temporal metrics associated with proficiency but did not examine kinematic metrics (21).

The most commonly measured kinematic metric was x-factor (angular separation between the pelvis and trunk) (3,9–11,13,17–19,23), with several studies also measuring trunk rotation velocity (3,9,10,13,18,23). Several studies have shown that x-factor is related to proficiency, specifically, ball speed (3,18), clubhead speed (9), and handicap index (17,23). Trunk rotation velocity was also related to ball speed in some studies (3,18).

Fewer studies have examined kinetic metrics associated with proficiency. More proficient golfers have also been shown to have greater ground reaction forces (GRF) on the lead foot during the downswing (3,6,17,19). Combinations of kinematic and kinetic metrics have been shown to be predictive of golf proficiency. Chu et al. (3) examined combinations of kinematic and kinetic factors related to ball speed but limited the analysis to combinations of metrics occurring at a single point in the golf swing. For example, 74% of the variability in ball speed could be explained by the combination of 10 metrics occurring 50 milliseconds before ball impact: 5 positional metrics (forward trunk tilt, lateral trunk bend, lead arm angle, wrist hinge angle, upper trunk rotation angle), 3 velocity metrics (lateral trunk flexion velocity, trunk rotation velocity, wrist hinge velocity), and 2 force metrics (lead foot GRF, rear foot rate of unloading). The explained variance in ball speed was less using combinations of metrics occurring at the top of the backswing ($R^2 = 44\%$), downswing acceleration ($R^2 = 66\%$), or ball impact ($R^2 = 51\%$). Combinations of factors across all phases of the swing were not assessed.

The temporal relationship between discrete kinematic or kinetic metrics has not been studied extensively with respect to golf proficiency. Peak lead foot GRF was shown to occur earlier in more proficient golfers (21). Similarly, for more proficient golfers, the peak velocities of the proximal segments were shown to occur earlier in the downswing (23). However, peak velocities of the distal segments occurred later in the downswing compared with less proficient golfers (23). It was unclear from these studies (21,23) whether the sequencing of the swing events is affected by

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golf proficiency. Although the kinematic sequencing of the golf swing is well described as a proximal to distal progression of body segment velocities (7,22), the sequence of positional changes (e.g., pelvis and trunk rotation), velocity changes (e.g., pelvis, trunk, arm), and force changes (e.g., weight shifts between the lead and rear feet) and their respective temporal relationships have not been examined in relation to proficiency.

Therefore, the purpose of this study was to determine which metrics best identified golf proficiency and which combinations of metrics across the swing sequence best explained proficiency. It was hypothesized that discrete kinematic, kinetic, and temporal metrics would vary depending on proficiency and that combinations of metrics from each category would explain specific proficiency metrics. It was also hypothesized that sequencing of kinematic and kinetic events through the golf swing would be more variable in the less proficient golfers.

Methods

Experimental Approach to the Problem

A cross-sectional approach was used to explore the relationship between golf swing biomechanics and indices of golf proficiency in a group of golfers with varying levels of proficiency. Kinematic, kinetic, and temporal metrics and their sequencing were collected for shots performed with a driver. Golfers were categorized as proficient, average, or unskilled based on a combination of their United States Golf Association (USGA) handicap index, their ball speed, and their total shot distance. All biomechanical metrics were compared between the proficiency groups. Regression analyses were used to identify combinations of metrics that best identified proficiency.

Subjects

A total of 33 male golfers were included in the study (age 37 ± 14 years, range 18–72 years; height 176 ± 7 cm; body mass 80.2 ± 16.6 kg; USGA index 8.1 ± 7.8). Inclusion criteria were (1) USGA handicap index no higher than 24 (2), currently playing golf regularly (at least 6 rounds a year) (3), currently uninjured, and (4) at least 18 years old. There was no upper age limit as long as the golfer met the other criteria. Female golfers were not included based on the presumption that there would be biomechanical differences between male and female golfers independent of golf proficiency. All subjects gave written informed consent, and the study was approved by the human research protection program at the Feinstein Institute for Medical Research, Northwell Health.

Previously published data for x-factor (3,9,17,18,23), trunk velocity (3,18), and GRF (3,6,19) were used to estimate the sample size required to have 80% power to detect differences between the proficiency groups at an alpha threshold of 0.05. It was estimated that an 11° difference in x-factor at the top of the backswing, a $113°\cdot s^{-1}$ difference in peak trunk velocity, and a difference of 32% of body mass in peak GRF could be detected with 11 subjects per group. Based on the typical mean values for these metrics, these effects represent a 20% difference in x-factor, an 18% difference in trunk velocity, and a 30% difference in GRF.

Procedures

Kinematic Analyses. Twenty-four retroreflective markers were placed on the lower extremities, arms, and trunk. The marker locations were as follows: C7 vertebra, right and left acromia, right and left medial elbow, right and left lateral elbow, right and left ulnar styloid, right and left distal radius, right and left anterior superior iliac spine, right and left posterior superior iliac spine, sacrum, right and left lateral femoral condyle, right and left lateral malleolus, right and left calcaneus, and right and left base of the fifth metatarsal. Five additional markers were placed on the golf club along the shaft and club head. The golf ball was also covered in retroreflective tape to determine the moment of impact with the club. Kinematic data were recorded with 10 infrared cameras at 500 Hz (BTS Bioengineering, Quincy, MA). After warm-up, subjects hit 5 shots with the driver, and the best 3 swings by distance were analyzed. Ball flight was measured with a radar-based ball launch monitor (TrackMan Golf, Scottsdale, AZ) from which ball speed and total distance were recorded for categorizing proficiency.

A total of 9 positional metrics were recorded, 3 x-factor metrics and 6 hip range of motion (ROM) metrics. X-factor is defined as the separation between axial trunk and pelvis rotation. Peak x-factor, x-factor at the top of the backswing, and x-factor at ball impact were recorded. Hip ROM at the top of the backswing, at peak pelvis velocity, and at ball impact were recorded for the lead and back hip. Peak velocities for axial rotation of the pelvis, trunk, and lead arm were recorded. In addition, average acceleration from the top of the backswing to peak velocity was recorded for the pelvis and trunk. There was a total of 14 kinematic metrics (9 positional, 3 velocity, 2 acceleration).

Kinetic Analyses. Resultant GRF under the lead and back feet were recorded at 1,000 Hz, with 2 force plates (BTS Bioengineering, Quincy, MA). Peak GRF, GRF at the top of the backswing, and GRF at ball impact were recorded for the lead and back feet. Ground reaction forces in newtons was expressed as a percentage of body weight in newtons.

Temporal Metrics and Sequencing Analyses. The timings of kinematic and kinetic events in milliseconds were expressed relative to the time from the top of the backswing. In addition to the top of the backswing (time zero) and ball impact (final time), the timings of peak x-factor, peak pelvis, trunk and arm velocities, and peak GRF for the back and rear foot were identified.

Proficiency Metrics. Golf swing proficiency was defined by 3 factors: official golf handicap index, driving ball speed, and total driving distance. Golfers were divided into tertiles for each of the 3 factors: index <5, 5–11, >11; ball speed $>68.2\ m\cdot s^{-1}$; $68.2–60.0\ m\cdot s^{-1}$; $<60.0\ m\cdot s^{-1}$; and total distance >225 m, 225–205 m, <205 m. Players in the top tertile for at least 2 of the 3 factors and not in the bottom tertile for the other factor were defined as proficient golfers ($n = 11$). Players in the bottom tertile for at least 2 of the 3 factors and not in the top tertile for the other factor were defined as unskilled ($n = 11$). The remaining players were defined as average ($n = 11$). The rationale for choosing 3 groups was to be able to differentiate factors that identified proficient golfers (those significantly better than average and unskilled golfers) from factors that identified unskilled golfers (significantly worse than the average and proficient golfers).

Statistical Analyses

One-way analysis of variance was used to examine differences in position, velocity, force, and timing metrics between proficient, average and unskilled golfers, with Tukey's post hoc tests for pairwise comparisons between the groups where there was a significant F ratio. Metrics that were significantly different between proficient vs. average and unskilled golfers but not different between average and unskilled golfers were classified as identifying proficient golfers. Metrics that were significantly different between unskilled golfers vs. average and proficient golfers but not different between average and proficient golfers were classified as identifying unskilled golfers. Metrics that were significantly different between all 3 groups were classified as identifying all skill levels. Variables that were only significantly different between proficient and unskilled golfers were classified as identifying the extremes of ability only. Metrics that were significantly different between average and unskilled, or between average and proficient, but not different between proficient and unskilled were classified as having unclear identification. In the results tables, the terms "proficient," "unskilled," "all," "extremes only," and "unclear" are used to specify the statistical significance of the pairwise comparisons. Differences in sequencing between proficiency groups was assessed with χ^2 analyses comparing proportions of golfers within each group with specific sequences. Pearson's correlation coefficients were used to assess associations between biomechanical metrics and performance metrics. For multiple regression analyses, variables that had a bivariate relationship with the dependent variable with a p value of <0.100 were included as factors in the multiple regression in a stepwise manner. The r^2 and R^2 values are reported and represent the percentage of the variability in the dependent variable explained by independent variable (r^2) or combinations of variables (R^2). Mean ± SD is reported in the tables and text, and effect sizes are reported with 95% confidence intervals.

Results

Demographics of Proficiency Groups

Proficient golfers were younger than unskilled golfers (28 ± 6 years vs. 48 ± 15 years; $p < 0.001$), but age was not significantly different between proficient and average golfers (28 ± 6 years vs. 36 ± 12 years; $p = 0.206$) or between average and unskilled golfers (36 ± 12 years vs. 48 ± 15 years; $p = 0.065$). Proficient golfers were taller than average golfers (180 ± 4 cm vs. 173 ± 7 cm, $p = 0.03$) but not different from unskilled golfers (176 ± 6 cm, $p = 0.160$). Body mass was not different between the proficiency groups.

Ensemble averages of kinematic (x-factor and pelvis velocity) and kinetic (lead foot GRF) data for the 3 groups are displayed in Figure 1.

Kinematic Data

X-factor at the top of the backswing, peak x-factor, and x-factor at ball impact differed significantly between the groups ($p < 0.001$; Table 1). Unskilled golfers had lower x-factor at the top of the backswing than average golfers ($p = 0.002$; effect size 1.6, 0.4–2.9) and proficient golfers ($p < 0.001$; 2.0, 0.7–3.2) and lower peak x-factor than average golfers ($p = 0.005$; effect size 1.5, 0.3–2.7) and proficient golfers ($p < 0.001$; effect size 2.1, 0.8–3.4). Proficient golfers had a higher x-factor at ball impact than average golfers ($p = 0.001$; effect size 1.7, 0.4–2.9) and unskilled golfers ($p < 0.001$; effect size 2.6, 1.2–4.0).

Hip ROM did not differ between the proficiency groups through the golf swing. At the top of the backswing, the back hip was internally rotated (proficient 26 ± 10°, average 29 ± 17°, unskilled 24 ± 18°; $p = 0.751$), and the lead hip was externally rotated (proficient 28 ± 8°, average 30 ± 14°, unskilled 29 ± 13°; $p = 0.920$). At peak pelvis velocity, the back and lead hips were slightly externally rotated (back hip: proficient 7 ± 6°, average 4 ± 12°, unskilled 5 ± 16°; $p = 0.819$; lead hip: proficient 10 ± 8°, average 7 ± 13°, unskilled 1 ± 13°; $p = 0.742$). At ball impact, the back hip was externally rotated (proficient 27 ± 15°, average 20 ± 11°, unskilled 21 ± 13°; $p = 0.429$) and the lead hip was

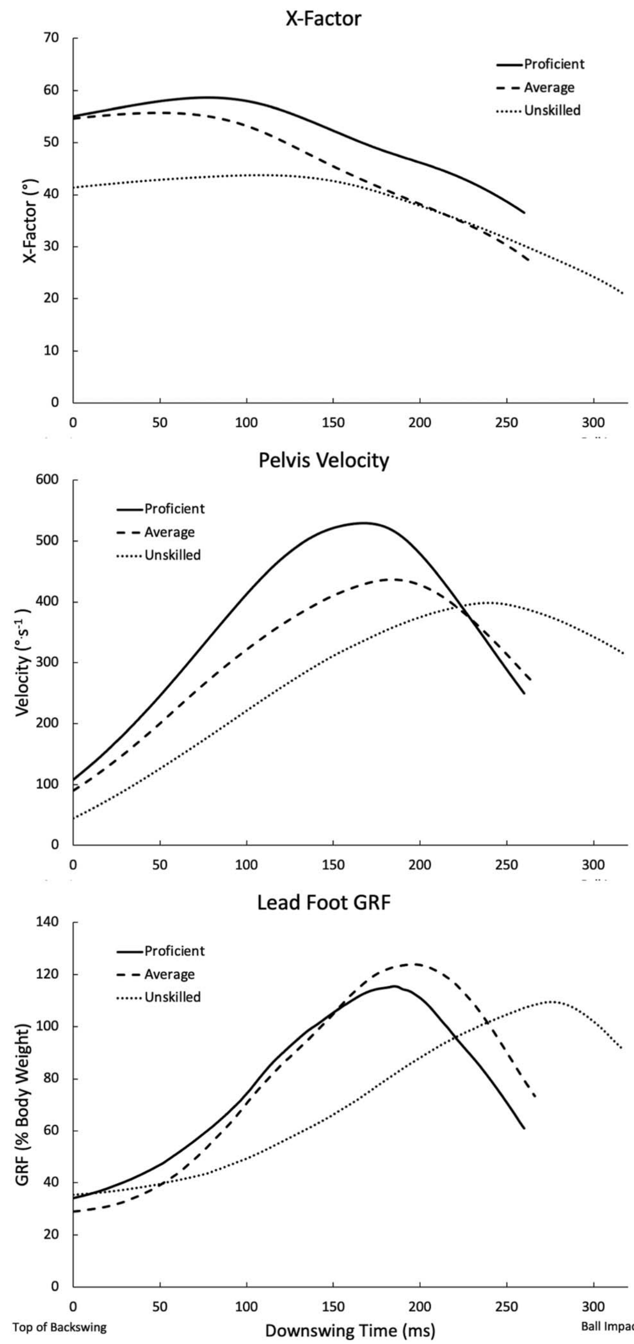

Figure 1. Ensemble averages of x-factor, pelvis velocity, and lead foot GRF for proficient, average, and unskilled golfers. Data from the top of the backswing to ball impact are shown. Because different events occur at different times between individuals within each group, the displayed values in this figure will not match the group means displayed in the tables for the same metrics. GRF = ground reaction forces.

Table 1

X-factor values for golfers differentiated by proficiency.*

	X-factor		
	Top of backswing	Peak	Impact
Proficient golfers	56 ± 6°	62 ± 5°	36 ± 5°
Average golfers	54 ± 11°	57 ± 10°	27 ± 6°
Unskilled golfers	41 ± 6°	46 ± 6°	21 ± 6°
ANOVA *p* value	$p < 0.001$	$p < 0.001$	$p < 0.001$
Group(s) identified	Unskilled	Unskilled	Proficient

*ANOVA = analysis of variance.

Table 2

Velocity data for golfers differentiated by proficiency.*

	Velocities (°·s^{-1})		
	Peak pelvis	Peak trunk	Peak arm
Proficient golfers	526 ± 83	604 ± 88	1,167 ± 107
Average golfers	474 ± 92	573 ± 69	1,161 ± 263
Unskilled golfers	413 ± 71	538 ± 92	1,010 ± 210
ANOVA *p* value	$p = 0.012$	$p = 0.199$	$p = 0.144$
Group(s) identified	Extremes only	None	None

*ANOVA = analysis of variance.

slightly internally rotated (proficient 5 ± 9°, average 3 ± 9°, unskilled 6 ± 7°; $p = 0.752$).

Peak pelvis velocity differed between the groups ($p = 0.012$), but there was no significant effect of proficiency on peak trunk velocity ($p = 0.199$) and peak arm velocity ($p = 0.144$; Table 2). Proficient golfers had a higher pelvis velocity than unskilled golfers ($p = 0.009$; effect size 1.4, 0.2–2.5).

Average pelvis and trunk acceleration from the top of the backswing to their respective peak velocities differed significantly between the proficiency groups (pelvis $p = 0.032$, trunk $p = 0.035$; Table 3). Pelvis and trunk accelerations were higher for proficient vs. unskilled golfers (pelvis: $p = 0.025$; effect size 1.2, 0.4–2.3; trunk: $p = 0.030$; effect size 1.1, 0.0–2.3). Similarly, average pelvis and trunk deceleration, from the respective peak velocities to ball impact, differed significantly between the groups (pelvis $p = 0.008$, Trunk $p = 0.001$; Table 3). Proficient golfers had greater pelvis deceleration than unskilled golfers ($p = 0.006$; effect size 1.4, 0.6–2.3) and greater trunk deceleration than average golfers ($p = 0.033$; effect size 1.1, 0.1–2.3) and unskilled golfers ($p = 0.001$; effect size 1.7, 0.5–2.9).

Kinetic Data

None of the GRF values on the back and lead feet differed between the golf proficiency groups (Table 4a,b). However, unweighting of the lead foot from peak GRF to ball impact differed between the proficiency groups ($p = 0.008$). Proficient golfers unweighted their lead foot more than unskilled golfers ($p = 0.008$; effect size 1.4, 0.2–2.6) before ball impact.

Peak trunk velocity preceded peak lead arm velocity for 9 of 11 proficient golfers, 8 of 11 average golfers, and 7 of 11 unskilled golfers, occurring 15 ± 31, 15 ± 33, and 14 ± 42 milliseconds before peak lead arm velocity for the proficient, average, and unskilled golfers, respectively.

The time from the top of the backswing to peak trunk velocity, peak lead foot GRF, and peak arm velocity was longer for less proficient golfers ($p = 0.024$, $p = 0.028$ and $p = 0.017$, respectively; Table 5). Unskilled golfers took longer to reach peak trunk velocity compared with proficient golfers ($p = 0.037$; effect size 1.1, 0.0–2.2) and took longer to reach peak lead foot GRF and peak arm velocity compared with average golfers (peak lead foot GRF: $p = 0.047$; effect size 1.1, −0.1 to 2.2; peak arm velocity: $p = 0.041$; effect size 1.1, 0.0–2.2) and proficient golfers (peak lead foot GRF: $p = 0.055$; effect size 1.0, −0.1 to 2.2; peak arm velocity: $p = 0.027$; effect size 1.2, 0.0–2.2).

Predictors of Golf Index, Ball Speed, and Total Driving Distance

X-factor at impact was the strongest predictor of golf index ($r^2 = 0.541$), total driving distance ($r^2 = 0.573$), and ball speed ($r^2 = 0.648$; Table 6). For golf index, the addition of peak lead arm velocity improved the prediction ($R^2 = 0.627$). Adding age as a factor to the regression analysis slightly changed the prediction of golf index

$$\left[R^2 = 682;\ \text{Golf Index} = (-0.663\cdot\text{X} - \text{Factor at Impact}) + (0.147\cdot\text{age}) + (-0.009\cdot\text{Peak Lead Arm Velocity}) + 8.1\right].$$

For total driving distance, the addition of peak lead arm velocity ($R^2 = 0.696$) and peak lead foot GRF ($R^2 = 0.743$) improved the prediction. Adding age as an independent factor did not change the prediction of driving distance. For ball speed, multiple factors improved the prediction (peak pelvis velocity $R^2 = 0.740$, time to peak lead arm velocity $R^2 = 0.785$, time to max trunk velocity $R^2 = 0.816$, peak lead foot GRF $R^2 = 0.845$). Adding age as an independent factor did not change the prediction of ball speed.

Timing and Sequencing Data

The sequence of swing events was consistent regardless of swing proficiency ($p > 0.05$ for all sequencing analyses). For all golfers, peak GRF on the back foot preceded the top of the backswing, and all other events occurred after the top of the backswing (Figure 2). Peak X-factor preceded peak pelvis velocity for all players. Peak pelvis velocity preceded peak trunk velocity for all proficient golfers, for 9 of 11 average golfers, and for 10 of 11 unskilled golfers. Peak trunk velocity and peak lead foot GRF occurred almost simultaneously: peak lead foot GRF occurred 0.6 ± 17 milliseconds and 7 ± 32 milliseconds before peak trunk velocity for proficient and average golfers, respectively, and 5 ± 33 milliseconds after peak trunk velocity for unskilled golfers.

Discussion

As hypothesized, there were discrete differences between golf proficiency groups for kinematic metrics (3 positional metrics, 1 velocity metric, 4 acceleration metrics), kinetic metrics (1 GRF

Table 3
Acceleration data for golfers differentiated by proficiency.*†

	Average acceleration (°·s^{-2})		Average deceleration (°·s^{-2})	
	Pelvis	Trunk	Pelvis	Trunk
Proficient golfers	2,560 ± 760	3,017 ± 683	3,139 ± 1,489	3,214 ± 1,653
Average golfers	2,160 ± 676	2,748 ± 722	2,247 ± 1,435	1,752 ± 1,201
Unskilled golfers	1,757 ± 589	2,200 ± 731	1,294 ± 845	998 ± 923
ANOVA *p* value	$p = 0.032$	$p = 0.035$	$p = 0.008$	$p = 0.001$
Group(s) identified	Extremes only	Extremes only	Extremes only	Proficient

*ANOVA = analysis of variance.
†Average acceleration was computed from the velocity changes from the top of the backswing to the respective peak velocities. Average deceleration was computed from the velocity changes from the respective peak velocities to ball impact.

metric), and timing metrics (1 GRF and 2 velocity timing metrics). However, the sequencing of kinematic and kinetic metrics was not different between the groups. Two metrics distinguished proficient golfers from both average and unskilled golfers: (1) x-factor at ball impact for proficient golfers was 9° greater than average golfers and 15° greater than unskilled golfers and (2) trunk deceleration from peak trunk velocity to ball impact for proficient golfers was 83% higher than average golfers and 220% higher than unskilled golfers. Four metrics distinguished unskilled golfers from both average and proficient golfers: (1) x-factor at the top of the backswing for unskilled golfers was 13° lower than average golfers and 15° lower than proficient golfers, (2) peak x-factor for unskilled golfers was 11° lower than average golfers and 16° lower than proficient golfers, (3) peak lead foot GRF for unskilled golfers occurred 43% later than average golfers and 41% later than proficient golfers, (4) peak lead arm velocity for unskilled golfers occurred 32% later than average golfers and 35% later than proficient golfers. Six metrics distinguished proficient golfers from unskilled golfers but did not differentiate average golfers from either group (peak pelvis velocity, pelvis and trunk acceleration, pelvis deceleration, lead foot unweighting, timing of peak trunk velocity). None of the hip ROM metrics and none of the back foot GRF metrics differed between the proficiency groups. In addition, peak trunk and lead arm velocity, peak lead foot GRF, lead foot GRF at the top of the backswing and at impact, and the timing of peak back foot GRF, peak x-factor, peak pelvis velocity, and ball impact did not differ between the proficiency groups.

Several studies have previously shown x-factor at the top of the backswing and peak x-factor to be important contributors to golf proficiency (3,9,10,18,23). Only one of these studies examined x-factor at impact (23), and the results were very comparable to this study. Four groups of 18 golfers were classified as professional, low handicap, mid, and high handicap. X-factor at the top of the backswing was greater for professionals vs. high handicap golfers (60 ± 7° vs. 49 ± 12°) with no differences between the other groups (23). In this study x-factor at the top of the backswing was also greater for proficient vs. unskilled golfers (56 ± 6° vs. 41 ± 6°). More importantly, x-factor at impact better discriminated groups in both studies. Four of 6 possible comparisons of x-factor at impact were significantly different between the groups in the study by Zheng et al. (23): 24 ± 10°, 22 ± 6°, 15 ± 5°, and 9 ± 9° for professional, low, mid, and high handicap groups. In this study, x-factor at impact for the proficient golfers (36 ± 6°) was greater than that for average (27 ± 6°) and unskilled (21 ± 6°) golfers.

The delay in developing peak lead arm velocity and peak lead food GRF for unskilled vs. proficient golfers is consistent with other studies examining kinematic timing (23) and kinetic timing (21). Similarly, higher pelvis rotation velocity in more proficient golfers seen in this study is consistent with previous work (18). Peak pelvis rotation velocity was 21% higher in golfers with a high ball speed vs. low ball speed in a large sample of golfers with an average handicap index of 8.1 ± 7.3 and an average ball speed of 64.9 ± 6.8 m·s^{-1} (18). In this study, average handicap index was 8.1 ± 7.8, ball speed was 63.6 ± 7.8 m·s^{-1}, and peak pelvis

Table 4
(A) GRF data for the back foot differentiated by proficiency. (B) GRF data for the lead foot differentiated by proficiency.*†

(A)	Back leg ground reaction force (% body mass): Peak	Top of backswing	Impact
Proficient golfers (%)	78.3 ± 6.0	58.1 ± 13.7	29.7 ± 17.4
Average golfers (%)	81.9 ± 6.6	59.0 ± 15.3	33.6 ± 19.4
Unskilled golfers (%)	75.4 ± 8.9	62.0 ± 13.5	32.3 ± 16.3
ANOVA *p* value	$p = 0.130$	$p = 0.800$	$p = 0.872$
Group(s) identified	None	None	None

(B)	Lead leg ground reaction force (% body mass): Top of backswing	Peak	Impact	Unweighting
Proficient golfers (%)	33.0 ± 10.8	139.5 ± 19.6	63.3 ± 35.6	76.2 ± 36.5
Average golfers (%)	30.3 ± 10.8	136.1 ± 24.2	71.4 ± 29.8	64.7 ± 30.1
Unskilled golfers (%)	36.8 ± 16.0	120.1 ± 20.7	90.8 ± 16.6	28.8 ± 21.9
ANOVA *p* value	$p = 0.500$	$p = 0.096$	$p = 0.082$	$p = 0.008$
Group(s) identified	None	None	None	Extremes only

*GRF = ground reaction forces; ANOVA = analysis of variance.
†Unweighting refers to the decrease in GRF from peak to impact.

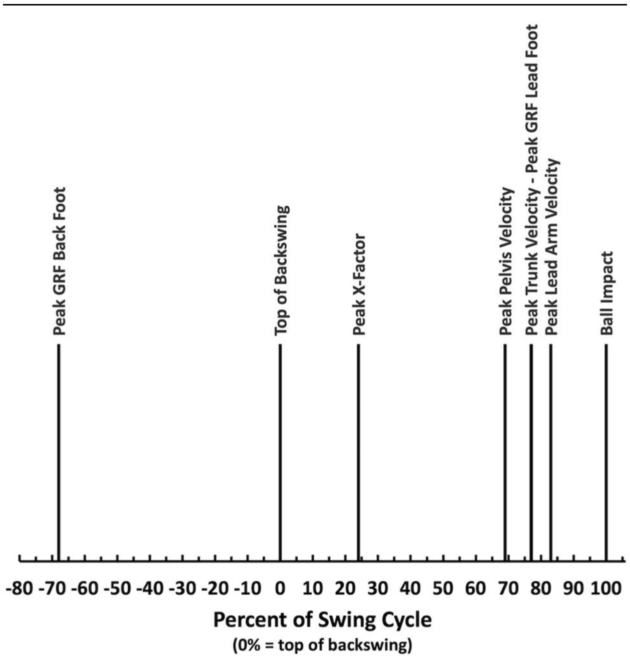

Figure 2. Sequence of kinetic and kinematic events for all golfers expressed as a percentage of the time from the top of the backswing to ball impact.

velocity was 27% higher in proficient vs. unskilled golfers. However, it is notable that trunk velocity was not different between the proficiency groups (12% nonsignificant difference between proficient and unskilled golfers), but in one previous study, trunk velocity was 30% higher in golfers with high vs. low ball velocity (18), and in another study, peak trunk rotation velocity correlated with ball speed (3).In this study, pelvis and trunk acceleration and deceleration better distinguished golfing proficiency than velocity measures, but other studies have not specifically studied acceleration and deceleration with respect to indices of proficiency.

The typical pattern for the forces generated at the feet during the golf swing was an unloading of the back foot during the downswing and a rapid loading of the front foot at the initiation of the downswing (Table 4a,b). Although these forces were not significantly different between the proficiency groups, it was notable that peak GRF on the lead foot tended to be higher in proficient vs. unskilled golfers and GRF at impact tended to be lower in proficient vs. unskilled golfers. This reflected a pattern whereby the more proficient golfers rapidly loaded the lead foot at the initiation of the downswing (time from top of backswing to peak GRF was 192 ms for proficient golfers vs. 271 ms for unskilled golfers) but then unloaded it before ball impact (proficient golfers unweighted their lead foot by 76% of body mass vs. 29% for unskilled golfers). A similar pattern has been reported previously (3), where lead foot GRF 40 milliseconds before ball impact positively correlated with ball speed and the rate of unloading at ball impact also positively correlated with ball speed.

It is important to understand the golf swing as a stretch-shortening cycle (SSC) movement. The stretch phase of an SSC movement serves to optimally use the elastic properties of the series elastic component of skeletal muscle to augment the shortening (propulsive) phase (12). The sequence of kinematic events in the golf swing explains the SSC behavior. Axial separation between the pelvis and trunk (x-factor) during the backswing transfers potential elastic energy to the trunk. The downswing is initiated by forward axial pelvic rotation, which further separates the pelvis and trunk (peak x-factor). This has been referred to as x-factor stretch (9,10,13). The potential elastic energy generated by the x-factor provides noncontractile energy to increase trunk acceleration. To that end, in this study, average trunk acceleration from the top of the backswing to peak trunk rotation velocity correlated with x-factor at the top of the backswing ($r = 0.42$, $p = 0.015$) and with peak x-factor ($r = 0.553$, $p < 0.001$). These associations highlight the contribution of x-factor to the forces accelerating the trunk.

The proximal to distal progression of rotational velocities is the primary feature of the kinematic sequence of the golf swing, whereby the pelvis reaches its peak axial rotation velocity before the trunk and peak trunk velocity precedes peak hand velocity (22). Less attention has been given to the actual deceleration of the proximal segment after it reaches its peak velocity. The deceleration of the proximal segments while the distal segments are accelerating is analogous to the action of a whip. The fact that the proficient golfers had greater trunk deceleration before ball impact than both average and unskilled golfers highlights the functional importance of this whip action. In fact, the only other metric that specifically distinguished proficient golfers from both average and unskilled golfers was x-factor at impact. The ability to decelerate the trunk before impact likely maintains the separation of the pelvis and trunk, and it follows that trunk deceleration correlated with x-factor at impact ($r = 0.594$, $p < 0.001$). For proficient golfers, trunk deceleration was 2% higher than pelvis deceleration, but for average and unskilled golfers, trunk deceleration was 22 and 23% lower than pelvis deceleration, respectively (Table 3). Furthermore, for proficient golfers, trunk deceleration was 7% greater than trunk acceleration, but for average and unskilled golfers, trunk deceleration was 36 and 55% lower than trunk acceleration, respectively (Table 3).

The fact that the proficient golfers were younger than the unskilled golfers is a limitation. Thus, the differences in biomechanical metrics between proficiency groups may in part

Table 5

Timing of the kinetic and kinematic events differentiated by proficiency.*

	Timing of kinetic and kinematic events relative to top of backswing (ms)						
	Back foot peak GRF	Peak X-Factor	Peak pelvis velocity	Peak trunk velocity	Peak lead foot GRF	Peak arm velocity	Impact
Proficient golfers	−155 ± 218	69 ± 41	173 ± 30	192 ± 34	192 ± 42	207 ± 40	266 ± 29
Average golfers	−281 ± 198	35 ± 61	175 ± 47	197 ± 49	190 ± 55	212 ± 46	260 ± 37
Unskilled golfers	−138 ± 285	99 ± 109	236 ± 100	265 ± 98	271 ± 111	279 ± 87	317 ± 102
ANOVA p value	$p = 0.317$	$p = 0.160$	$p = 0.053$	$p = 0.024$	$p = 0.028$	$p = 0.017$	$p = 0.093$
Group(s) identified	None	None	None	Extremes only	Unskilled	Unskilled	None

*GRF = ground reaction forces; ANOVA = analysis of variance.

Table 6

Multiple regression analyses of biomechanical predictors of performance metrics.*†

Performance metric		Step 1	Step 2	Step 3	Step 4	Step 5
Golf index	Predictor variable	*X-factor at impact*	*Peak lead arm velocity*			
	R^2 value (% explained)	54.1%	62.7%			
	Regression equation	*(− 0.621·x-factor at impact) + (− 0.011·peak lead arm velocity) + 37.7*				
Total distance (m)	Predictor variable	*X-factor at impact*	*Peak lead arm velocity*	*Peak lead foot GRF*		
	R^2 value (% explained)	57.3%	69.6%	74.3%		
	Regression equation	*(2.22·X-factor at impact) + (0.042·peak lead arm velocity) + (0.304·peak lead foot GRF) + 62.8*				
Ball speed ($m \cdot s^{-1}$)	Predictor variable	*X-factor at impact*	*Peak pelvis velocity*	*Time from top of backswing to peak lead arm velocity*	*Time from top of backswing to peak trunk velocity*	*Peak lead foot GRF*
	R^2 value (% explained)	64.8%	74.0%	78.5%	81.6%	84.5%
	Regression equation	*(0.533·x-factor at impact) + (0.019·peak pelvis velocity) − (63.3·time from top of backswing to peak lead arm velocity) + (46.8·time from top of backswing to peak trunk velocity) + (0.066·peak lead foot GRF) + 35.5*				

*GRF = ground reaction forces.
†For regression equations x-factor is in °, velocity is in $° \cdot s^{-1}$, time is in seconds, GRF is % body mass.

reflect age effects. However, in the multiple regression analyses, age did not contribute to the explained variance in ball speed or driving distance. Age did contribute to the explained variance in golf handicap index but not substantially. The combination of x-factor at impact and peak lead arm velocity explained 67.2% of the variability in handicap index. Adding age to the analysis only increased the explained variance to 68.2%. Another limitation was the exclusion of female golfers because this limits the generalizability of the findings. However, it is likely that the biomechanical factors determining golf proficiency differ between male and female golfers, and this should be addressed in future research. In addition, only the biomechanics of the swing with a driver were examined. Whether these relationships to proficiency are seen with swings using other clubs remains to be determined.

Several kinematic, kinetic, and timing metrics effectively identified proficient and unskilled golfers. When looking at the specific indices of golf proficiency, 85% of the variability in ball speed was explained by a combination of kinematic (x-factor at impact and peak pelvis velocity), kinetic (peak lead foot GRF), and timing metrics (the timing of peak trunk and arm velocity). Similarly, Chu et al. (3) reported that 74% of the variability in ball speed was explained by 8 kinematic metrics and 2 kinetic metrics (timing metrics were not assessed). Furthermore, in this study, 74% of the variability in total driving distance was explained by the combination of 2 kinematic metrics (x-factor at impact and peak lead arm velocity) and 1 kinetic metric (peak lead foot GRF). For handicap index, only 2 metrics combined to explain 63% of the variability in handicap, both were kinematic metrics (x-factor at impact and peak lead arm velocity). X-factor at impact was the strongest predictor of all 3 performance metrics and distinguished proficient golfers from average and unskilled golfers.

Practical Applications

Understanding the biomechanics of complex movements in sports can provide insights into how best to train athletes to optimize performance. For example, in baseball pitching, peak trunk axial rotation velocity was the best predictor of ball velocity (20). The practical implication of this finding was that training strategies to improve trunk rotation velocity could theoretically improve ball velocity without having to stress the shoulder and elbow (20). The fact that x-factor at impact and trunk deceleration identified golf proficiency points to the potential of axial trunk rotation training to improve golf performance. For example, the seated medicine ball throw, a trunk rotation strengthening exercise, has been shown to be an effective exercise for improving driving distance in female golfers (8). Eccentrically biased trunk rotation exercises, including plyometric exercises, may be effective in improving golf proficiency. Golf-specific training programs have been effective in improving indices of golf performance (1,5,14), but it has been acknowledged that the optimal program will be dependent on the skill level of the player and their training status (4). Hip and trunk axial rotation flexibility have been shown to be strongly related to golf proficiency (15). Training programs that address the segmental axial motions of the hips, pelvis, and trunk may be optimal for improving golf performance.

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