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Rotational Biomechanics of the Elite Golf Swing: Benchmarks for Amateurs

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The purpose of this study was to determine biomechanical factors that may influence golf swing power generation. Three-dimensional kinematics and kinetics were examined in 10 professional and 5 amateur male golfers. Upper-torso rotation, pelvic rotation, X-factor (relative hip-shoulder rotation), O-factor (pelvic obliquity), S-factor (shoulder obliquity), and normalized free moment were assessed in relation to clubhead speed at impact (CSI). Among professional golfers, results revealed that peak free moment per kilogram, peak X-factor, and peak S-factor were highly consistent, with coefficients of variation of 6.8%, 7.4%, and 8.4%, respectively. Downswing was initiated by reversal of pelvic rotation, followed by reversal of upper-torso rotation. Peak X-factor preceded peak free moment in all swings for all golfers, and occurred during initial downswing. Peak free moment per kilogram, X-factor at impact, peak X-factor, and peak upper-torso rotation were highly correlated to CSI (median correlation coefficients of 0.943, 0.943, 0.900, and 0.900, respectively). Benchmark curves revealed kinematic and kinetic temporal and spatial differences of amateurs compared with professional golfers. For amateurs, the number of factors that fell outside 1–2 standard deviations of professional means increased with handicap. This study identified biomechanical factors highly correlated to golf swing power generation and may provide a basis for strategic training and injury prevention.

Keywords: clubhead speed, free moment, X-factor

Golf swing power generation is a primary determinant of driving distance and can be estimated using clubhead speed at impact (CSI) (Ball & Best, 2007b; Fradkin et al., 2004a, 2004b; Nesbit, 2005; Sprigings & Mackenzie, 2002; Teu et al., 2006). Rotational biomechanics have been identified as a key element influencing power generation. Analysis of professional golf performance has previously focused on events that occur at specific time points, but none have reported benchmark curves demonstrating elite golf performance throughout the duration of the swing and in relation to phases of the golf swing (Ball & Best, 2007a, 2007b; Gluck et al., 2007; Hume et al., 2005; McLaughlin & Best, 1994; Teu et al., 2006; Zheng et al., 2008a, 2008b). Development of benchmark curves based on elite professionals can provide a basis for strategic training.

Professional golf instructors, as well as several studies, have emphasized the importance of absolute and relative pelvic and upper-torso rotation during the golf swing (Cheetham et al., 2000; Cochran et al., 1968; Hume et al., 2005; McLaughlin & Best, 1994; McLean, 1992, 1993; McLean & Andrisani, 1997; McTeigue, 1985; McTeigue et al., 1994; Zheng et al., 2008a). Whereas several studies have examined the *X-factor,* defined as "relative pelvic and upper-torso rotation," in golfers of different ages and skill levels, none have examined the *O-factor,* defined as "pelvic obliquity," which is also thought to influence power generation (Clarke, 2007; DeNunzio, 2007). The O-factor theory suggests that the angle of a golfer's hips in relation to the horizontal plane should be slightly positive (leading hip elevated) at address, neutral at the top of backswing, and progress to a very positive angle at impact. DeNunzio (2007) suggests that a greater O-factor will result in a higher CSI. In a similar fashion, it may be argued that shoulder obliquity, or the *S-factor,* may also contribute to CSI through rotation and lifting motion.

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Weight shift during the golf swing has been previously described (Barrentine et al., 1994; Budney & Bellow, 1979; Carlsoo, 1967; Cooper et al., 1974; Gatt et al., 1998; Kawashima et al., 1998; Koenig et al., 1994; Okuda & Armstrong, 2002; Vaughan, 1981; Wallace et al., 1990, 1994; Williams & Cavanagh, 1983); however, its impact on performance remains to be determined. A few studies have emphasized the functional importance of free moments (Barrentine et al., 1994; Koenig et al., 1994; Robinson, 1994), but only in a descriptive nature, and none have reported free moments of elite golf performance in relation to phases of the golf swing. Free moment reflects a rotational motion and provides a force that translates through the golfer into the ball.

A high incidence of golf-related injuries has been previously reported. Among the injuries reported have been those to the lower back (15–36%), shoulders (6–10%), wrists (13–36%), and elbows (7–50%) Gluck et al., 2007; Gosheger et al., 2003; Grimshaw et al., 2002; Hovis et al., 2002; Kim et al., 2004; Lindsay & Horton, 2002; McCarroll, 1996; McCarroll & Gioe, 1982; McHardy et al., 2006, 2007; Parziale, 2002; Parziale & Mallon, 2006; Pink & Jobe, 1991; Stover et al., 1976; Theriault & Lachance, 1998; Vad et al., 2004; Wadsworth, 2007). Mechanisms of injury tend to arise from either overuse, primarily in professionals, or trauma and improper swing biomechanics, primarily in amateurs (Batt, 1992, 1993; Finch et al., 1998; Gosheger et al., 2003; McHardy et al., 2006; Theriault & Lachance, 1998). For example, Lindsay and Horton (2002) found that golfers with lower back pain exhibited a "supramaximal" axial rotation of the trunk. Characterization of the elite golf swing through benchmark curves may help guide swing modifications to reduce the incidence of injury.

The purpose of this study was to determine biomechanical factors that may influence golf swing power generation. We hypothesized that selected biomechanical factors of free moment, X-factor, O-factor, and S-factor would be highly consistent among professional golfers and have strong correlations to CSI. Benchmark curves were then developed to better understand differences between amateur and professional golfers.

Methods

Subjects and Protocol

Ten professional and five amateurs (one low-handicap collegiate [handicap 4], one medium handicap [handicap 15], one high-handicap [handicap 30], and two novices [handicap unknown; they do not play regularly]) right-handed male golfers were tested in the Motion & Gait Analysis Laboratory at Lucile Packard Children's Hospital (Stanford University, Palo Alto, CA). Professional and amateur golfers were similar in age (31.0 ± 5.9 years vs. 28.4 ± 6.9 years), height (1.83 ± 0.07 m vs. 1.78 ± 0.03 m), and weight (85.9 ± 11.5 kg vs. 77.3 ± 8.9 kg). The study was approved by the Institutional Review Board, Stanford University, and consent was obtained from participants. Forty-two reflective markers were placed on the subjects' bodies, using a combination of the Helen Hayes marker set and an upper-body marker set (Aguinaldo et al., 2007; Kadaba et al., 1990). Three markers were also placed on the participant's golf club (proximal, middle, and distal shaft), and a plastic practice ball was wrapped in light-reflective tape and placed on a synthetic grass mat. Each subject performed three swings of different efforts (easy, medium, and hard) using his personal 5-iron club. Kinematic data were collected using an eight-camera optometric system for three-dimensional motion analysis (Motion Analysis Corporation, Santa Rosa, CA) at a sampling rate of 240 Hz. The average three-dimensional residual error for the motion capture system was 1.2 ± 0.6 mm, which was the degree of accuracy in which the system could reconstruct the location of each marker in the capture volume. Ground reaction force and free moment data were collected using a 40 cm × 60 cm multicomponent, six degrees-of-freedom force plate (Bertec Corporation, Columbus, OH) at a sampling rate of 2400 Hz. The kinetic data were simultaneously recorded as an analog input channel into the EVaRT system (Motion Analysis Corporation, Santa Rosa, CA).

For each professional golfer, the two best trials with minimal marker dropout were processed. For amateur golfers, the two best trials of the hard swings were analyzed. Data from the markers located on the body were filtered using a Butterworth filter with a cutoff frequency of 12 Hz. Data from markers on the ball and clubhead were not smoothed. Golfers performed the swings in a nonrandomized order from easy to hard, and were given verbal cues before each swing. The interpretation of what constituted an easy, medium, and hard swing was left to the discretion of the golfer. Golf swings were analyzed using in-house algorithms written in Microsoft Excel 2002. Swing phases were defined based on clubhead and ball kinematics. The rising clubhead initiated backswing when velocity in the vertical direction exceeded 0.2 m/s (Figure 1). The initiation of downswing was defined by the transition of the clubhead direction at the top of backswing. Impact was defined as the time point immediately preceding the initial increase in ball velocity.

The algorithms used golf swing data files to calculate pelvic and upper-torso rotation angles with respect to the intended line of flight and projected into the horizontal plane, peak X-factor during the golf swing, X-factor at impact, O-factor (pelvic obliquity), S-factor (shoulder obliquity), peak ground reaction free moment, peak clubhead speed, and CSI. The X-factor was calculated as the angle between a line defined by the right and left anterior superior iliac spines (i.e., pelvis) and a line defined by the right and left acromion processes (i.e., upper torso) projected into the horizontal plane. This method is standard with many previous studies (Adlington, 1996; Burden et al., 1998; Grimshaw & Burden, 2000; Lemak et al., 1994; Lephart et al., 2007; McLean, 1992; McLean & Andrisani, 1997; McTeigue et al., 1994; Zheng et al.,

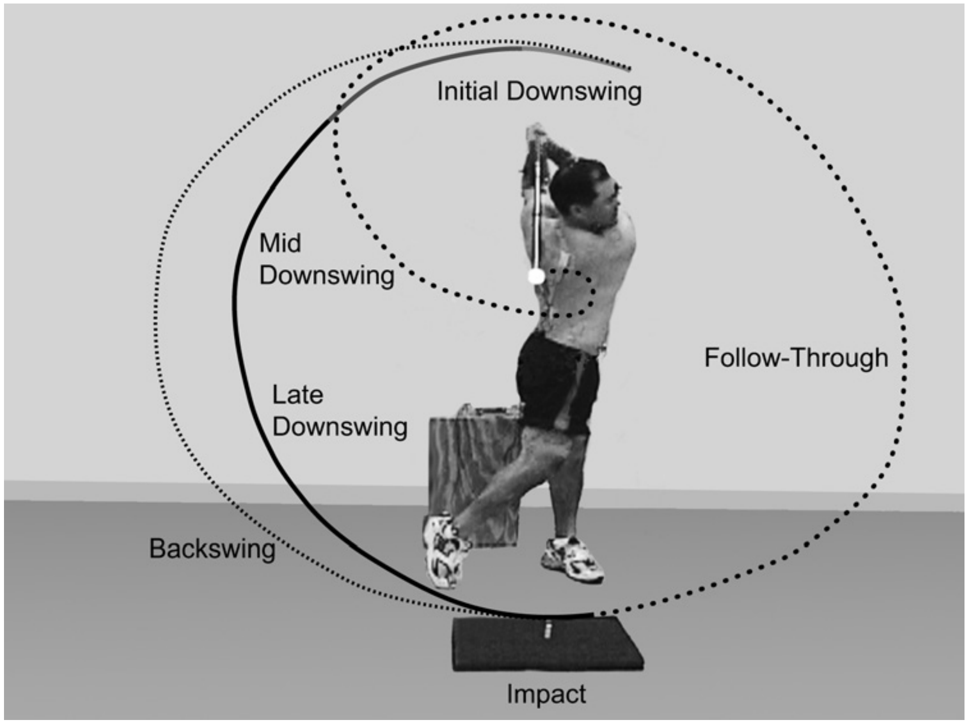

Figure 1 — The primary phases of the golf swing as determined by clubhead position were address, backswing, downswing, impact, and follow-through.

2008a). The O-factor was calculated as the angle between a 3-D line defined by the right and left anterior superior iliac spines and the horizontal plane. The S-factor was calculated as the angle between a 3-D line defined by the right and left acromion processes and the horizontal plane. Clubhead speed at impact was calculated using the linear 3-D velocity of the reflective marker placed on the most distal point of the club shaft at the time point immediately preceding impact. The free moment was measured as the ground reaction moment in the vertical axis (vector along the z-axis, extending from the floor to the ceiling) about the subject's center of pressure with both feet, in athletic shoes, on the force plate. Free moment was divided by body mass to normalize for subject size due to the influence of mass on frictional forces which contributed to the ground reaction free moment.

Benchmark Curves

Biomechanical factors of the professional golfers' hard swings were averaged first within subjects, and then between subjects to generate mean ± *SD* normal curves. Each swing was normalized to a golf cycle phase from the beginning of backswing (0%) to ball impact (100%). The end of follow-through (140%) was defined by the local minimum of vertical clubhead displacement after the club swung around the body during follow-through. Amateur swings were graphed over the professional normal curves for comparison. Swing cycle normalizations and curves were generated using in-house algorithms written in MATLAB (The MathWorks, Natick, MA).

Statistical Analysis

Statistical analyses of the professional golf swing data were performed using SPSS v15.0 (SPSS Inc., Chicago, IL). Mean values of biomechanical parameters within each level of effort were calculated for comparison between easy, medium, and hard swings among subjects. Coefficients of variation (Cv) were computed as the ratio of the standard deviation to the mean for easy, medium, and hard swings. Significant increases from easy to medium to hard swings were analyzed using nonparametric related samples Friedman ranks tests ($\alpha = 0.05$). Individual differences between easy and hard, easy and medium, and medium and hard swings were analyzed using nonparametric related samples Wilcoxon signed ranks tests ($\alpha = 0.05$). Correlations were computed within subjects between peak X-factor and CSI, X-factor at impact and CSI, peak free moment per kilogram and CSI, peak pelvic rotation and CSI, peak upper-torso rotation and CSI, peak S-factor and CSI, S-factor at impact and CSI, peak O-factor and CSI, and O-factor at impact and CSI using nonparametric two-tailed Spearman correlations ($\alpha = 0.05$). Where appropriate, data are reported as means ± 1 *SD*.

Results

Professional Golfers

For the professional golfers, backswing began with a clockwise rotation of the pelvis and upper torso in the horizontal plane (Figure 2, top panel). Downswing was initiated by the reversal of pelvic rotation followed by a reversal of upper-torso rotation (Figure 2, top panel). Peak free moment per kilogram occurred in early downswing (Figure 2, bottom panel).

Peak free moment per kilogram, peak X-factor, and peak S-factor were highly consistent among the professional golfers (Table 1) and were very strongly correlated to CSI within subjects (Table 2). Peak X-factor occurred just before peak free moment in all swings (Figure 2, bottom panel). Peak X-factor was more highly predictive of CSI than either peak upper-torso rotation or peak pelvic rotation alone (Table 2). X-factor at impact was also highly correlated to CSI (Table 2). S-factor at impact was less predictive of CSI than peak S-factor (Table 2). O-factor at impact and peak O-factor were less consistent (Table 1) and not as predictive of CSI as peak free moment per kilogram, X-factor at impact, peak X-factor, and peak S-factor (Table 2).

All biomechanical parameters increased from easy to medium to hard swings among professional golfers (Table 3). Summary statistics indicated that there was a significant linear increase in clubhead speed at impact, peak free moment per kilogram, X-factor at impact, peak X-factor, peak upper-torso rotation, peak S-factor, and O-factor at impact from easy to medium to hard swings.

Amateurs Versus Professional Golfers

The number of biomechanical factors during amateur hard swings that fell outside both one and two standard deviations of mean values for professional *hard* golf swings increased with handicap (Table 4). Benchmark curves of professional golfers are shown in Figure 3 in comparison with hard swings of the amateur golfers. Impact occurs at 100% percent of the cycle. For professional golfers, the mean ± 1 *SD* for biomechanical parameters are shown throughout the duration of the golf swing and demonstrate a narrow range of values (Figure 3). Kinematic and kinetic patterns of individual amateurs varied widely and indicated where they deviated from the professional means.

Discussion

This study analyzed the sequences of key rotational biomechanics during the professional golf swing and their relationship to power generation. Backswing began with a clockwise rotation of the pelvis and upper torso in the horizontal plane. Pelvic rotation reversed direction immediately before the beginning of downswing, and was followed by a reversal of upper-torso rotation (Figure 2, top panel). Similarly, other studies have found that pelvic transition occurred before upper-torso transition, serving to increase the X-factor during the early part of the downswing (Adlington, 1996; Burden et al., 1998; Cheetham et al., 2000; Grimshaw & Burden, 2000; Hume et al., 2005; McTeigue et al., 1994; Rehling, 1955). The pelvis continued to lead the upper torso throughout downswing. At impact, the upper torso was relatively parallel to the intended line of flight and rotated beyond the pelvis during follow-through (Figure 2, top panel).

Peak X-factor occurred just before peak free moment in all trials of the professional golfers (Figure 2, bottom panel) in late backswing or early downswing. This suggests that peak X-factor may contribute to peak free moment as indicated by the very strong within-subject correlations (Table 2). The peak values of X-factor, upper-torso rotation, and pelvic rotation were highly consistent among golfers, and similar to previous studies (Adlington, 1996; Burden et al., 1998; Grimshaw & Burden, 2000; Lemak et al., 1994; Lephart et al., 2007; McLean, 1992; McLean & Andrisani, 1997; McTeigue et al., 1994; Wheat et al., 2007; Zheng et al., 2008a).

This study is the first to describe S-factor, or shoulder obliquity, during the golf swing. Peak S-factor occurred right after impact and was found to be highly consistent (Cv = 8.4%) among professional golfers. This study is also the first to quantify O-factor, or pelvic obliquity, during the golf swing. The O-factor has been previously described but not quantified (Clarke, 2007; DeNunzio, 2007). Peak O-factor occurred immediately after impact and was found to be consistent (Cv = 23.9%) among professional golfers, although not as highly consistent as S-factor. Given that peak X-factor was also highly consistent (Cv = 7.4%), these findings support the notion that that professional golf swings are highly consistent within the group (i.e., intergolfer consistency). This study did not measure intragolfer consistency.

Quantifiable differences between professional and amateur golfers emerged. As expected, the novices had more pronounced differences in biomechanical factors than did experienced amateurs when compared with professionals (Table 4). Benchmark curves (Figure 3) revealed differences in biomechanics between amateur and professional golfers that may provide a basis for strategic training. For example, the peak free moment of Novice #1 was reduced and delayed compared with the professionals. His X-factor was excessive in early backswing, but insufficient in downswing compared with professionals. Novice #2 had a reduced X-factor throughout backswing and downswing.

A number of golf swing biomechanical factors exhibited a significant linear increase from easy to medium to hard swings, including clubhead speed at impact, peak free moment per kilogram, X-factor at impact, peak X-factor, peak upper-torso rotation, O-factor at impact, and peak S-factor (Table 3). This suggests that these factors are essential to golf swing power generation and modulation of driving distance. However, for peak pelvic rotation, there was no significant linear increase from easy, medium, to hard swings (Table 3). This suggests

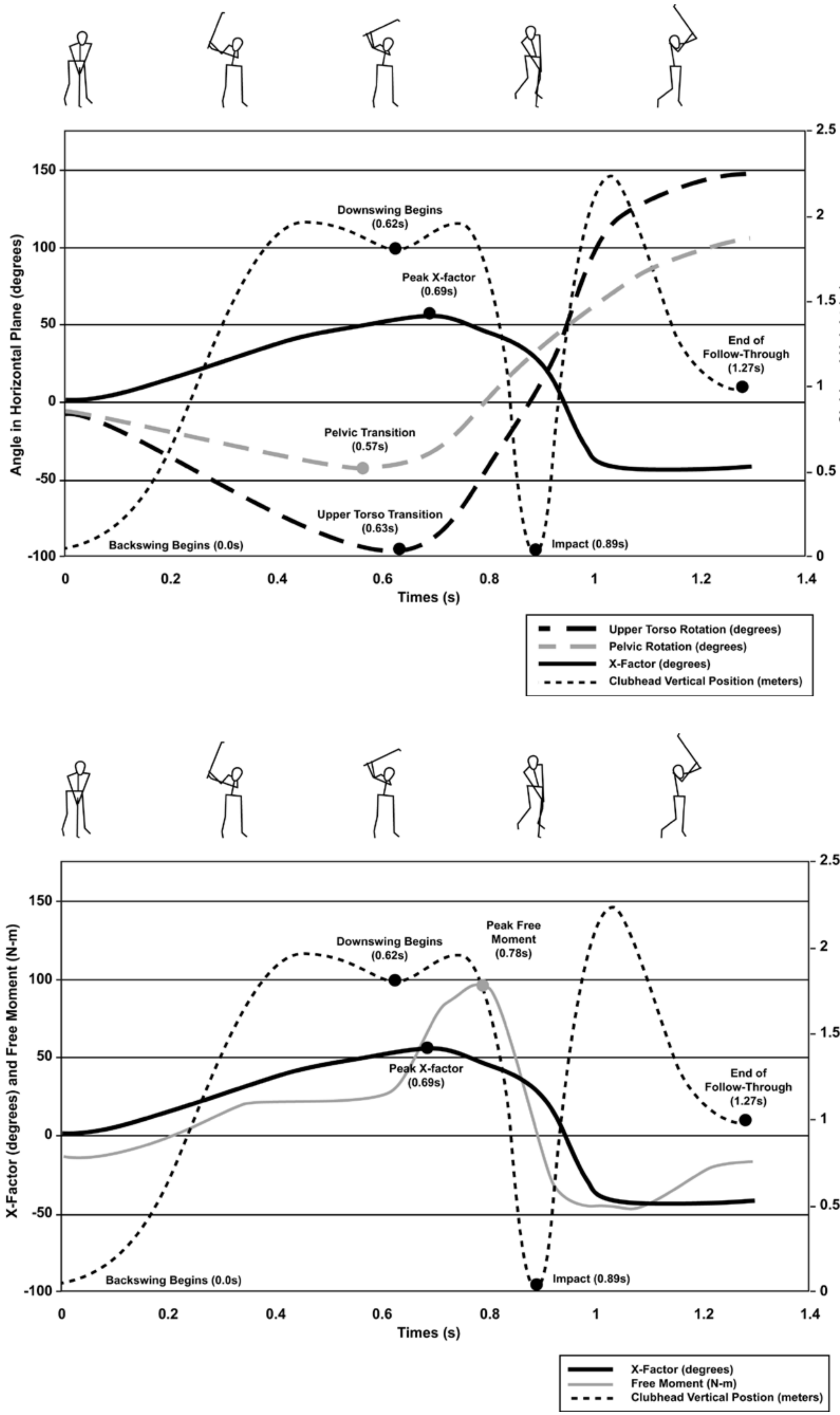

Figure 2 — Top panel: Sequence of key biomechanical events during a representative *hard* golf swing. The onset of backswing, downswing, and impact based on clubhead and ball kinematics are indicated by dots (•). Pelvic transition, upper-torso transition, and peak X-factor are also indicated. Bottom panel: Peak X-factor and peak free moment during a representative *hard* golf swing are indicated by dots (•). The onset of backswing, downswing, and impact based on vertical clubhead position are also indicated.

Table 1 Coefficients of variation (Cv) for mean biomechanical parameters of easy, medium, and hard swings among 10 professional golfers

Biomechanical Parameter	Easy % Cv	Medium % Cv	Hard % Cv
Clubhead Speed at Impact	9.7	5.0	5.9
Peak Free Moment/Mass	18.2	11.3	6.8
X-factor at Impact	23.7	15.3	19.0
Peak X-factor	8.0	7.5	7.4
Peak Upper-Torso Rotation	5.9	6.7	5.8
Peak Pelvic Rotation	13.0	13.3	12.4
S-Factor at Impact	13.3	12.4	12.4
Peak S-Factor	6.6	7.1	8.4
O-Factor at Impact	25.3	23.7	25.3
Peak O-Factor	20.9	21.3	23.9

Table 2 The relationship between rotational biomechanical parameters and clubhead speed at impact (CSI) within 10 professional golfers

Correlation to CSI	Within Subjects		
	Median Correlation Coefficient (ρ)	Mean Correlation Coefficient ± 1 *SD* (ρ)	Range
Peak Free Moment per Kilogram	0.943	0.914 ± 0.081	0.800 to 1.000
X-factor at Impact	0.943	0.863 ± 0.220	0.257 to 1.000
Peak X-factor	0.900	0.863 ± 0.134	0.543 to 1.000
Peak Upper-Torso Rotation	0.900	0.692 ± 0.356	0.086 to 1.000
Peak Pelvic Rotation	0.572	0.354 ± 0.564	–0.600 to 0.943
S-Factor at Impact	0.657	0.430 ± 0.544	–0.679 to 0.900
Peak S-Factor	0.750	0.702 ± 0.284	0.154 to 1.000
O-Factor at Impact	0.635	0.420 ± 0.646	–0.700 to 1.000
Peak O-Factor	0.600	0.312 ± 0.697	–0.886 to 0.943

that upper-torso rotation may contribute to X-factor to a greater degree than pelvic rotation.

Previous studies have reported peak and impact clubhead speeds ranging from 33 to 57 m/s (Fradkin et al., 2004a; Hume et al., 2005). Similarly, the CSI values of the professional golfers reported in this study fall within this range. The values reported here are near the lower end of this range, which may be explained by two reasons. First, the marker used to determine clubhead speed was on the most distal portion of the shaft, adjacent to the clubhead. Marker placement on the clubhead may have resulted in a higher linear clubhead velocity. Second, many previous studies used drivers instead of a 5-iron, as in this study. Given a constant angular velocity, a longer club, such as a driver, or more distal marker placement, would result in higher linear clubhead speeds.

The current study was limited in that data were necessarily collected in an indoor environment, where the true outcomes of shots were unknown. The study was designed to determine factors that contributed to power generation as indicated by clubhead speed at impact, a commonly used measure of power generation (Ball & Best, 2007b; Fradkin et al., 2004a, 2004b; Nesbit, 2005; Sprigings & Mackenzie, 2002; Teu et al., 2006), but not actual driving distance. It is also important to keep in mind that correlations, however strong, do not establish causality.

A precise understanding of optimal rotational biomechanics during the golf swing may guide swing modifications to help prevent or aid in the treatment of injury (Lemak et al., 1994; Parziale, 2002; Parziale & Mallon, 2006; Wadsworth, 2007). Previous studies have reported that poor golf swing mechanics are one of the leading causes of golf-related injuries, especially for the amateur player (McHardy et al., 2006; Theriault & Lachance, 1998). Low back injuries are one of the most prevalent injuries in golf (McHardy et al., 2006) and have been shown to be related to an excessive X-factor

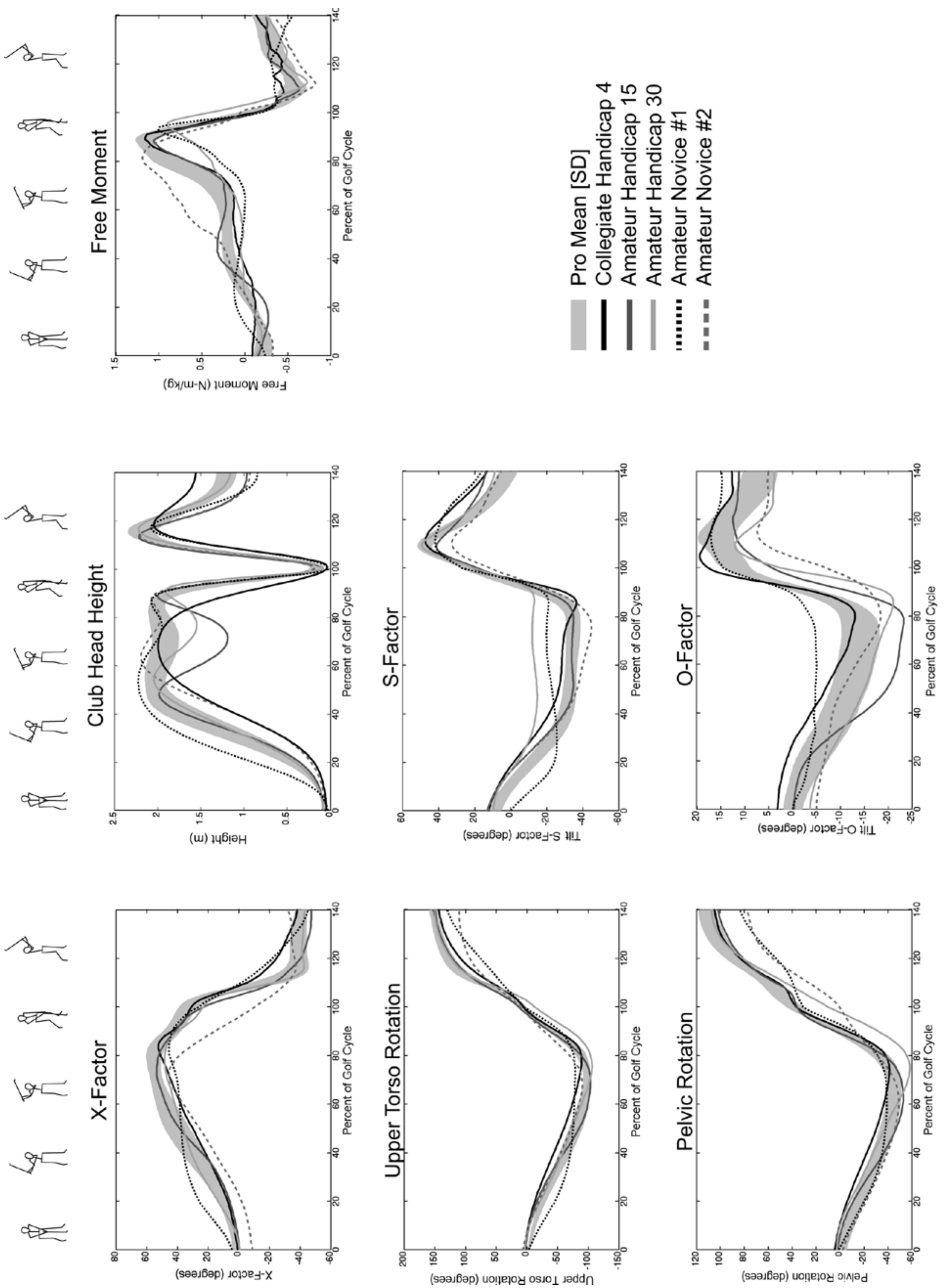

Figure 3 — Benchmark curves of mean rotational biomechanics for the hard golf swing of professionals compared with amateurs.

Table 3 Changes in biomechanical parameters for easy, medium, and hard swings among 10 professional golfers

Biomechanical Parameter	Easy	Medium	Hard	χ^2	Friedman (*p* value)	Wilcoxon (α = .05)
Clubhead Speed at Impact (m/s)	27.4 ± 2.6	31.6 ± 1.6	35.4 ± 2.1	20.0	<0.001	a, b, c
Peak Free Moment (N·m/kg)	0.83 ± 0.15	1.00 ± 0.11	1.19 ± 0.08	19.5	<0.001	a, b, c
X-factor at Impact (degrees)	24 ± 6	28 ± 4	33 ± 6	18.2	<0.001	a, b, c
Peak X-factor (degrees)	52 ± 4	54 ± 4	56 ± 4	18.2	<0.001	a, b, c
Peak Upper-Torso Rotation (degrees)	94 ± 6	97 ± 6	99 ± 6	11.4	0.003	a, b
Peak Pelvic Rotation (degrees)	44 ± 6	45 ± 6	46 ± 6	2.0	0.368	—
S-Factor at Impact (degrees)	24 ± 3	24 ± 3	25 ± 3	5.0	0.082	a, c
Peak S-Factor (degrees)	45 ± 3	46 ± 3	48 ± 4	12.8	0.002	a, b, c
O-Factor at Impact (degrees)	10 ± 3	11 ± 3	12 ± 3	9.7	0.008	a, c
Peak O-Factor (degrees)	15 ± 3	16 ± 3	16 ± 4	3.8	0.150	b

Note. Summary statistics are included for Friedman ranks test differences (chi-square values shown for n = 10, df = 2, α = .05) and significant Wilcoxon signed ranks test differences (α = .05) for (a) easy vs. hard, (b) easy vs. medium, and (c) medium vs. hard swings.

Table 4 Summary of biomechanical factors among professional (mean values, *n* = 10) and five amateur (individual values, *n* = 5) golfers; the amateurs consisted of novices (Nov) players with players with a handicap (Hcp).

Biomechanical Parameter	Pros	Hcp 4	Hcp 15	Hcp 30	Nov #1	Nov #2
Clubhead Speed at Impact (m/s)	35.4 ± 2.1	34.0	34.2	29.3**	30.2**	25.2**
Peak Free Moment/Mass (N·m/kg)	1.19 ± 0.1	1.19	1.07*	0.92**	1.03**	1.20
X-factor at Impact (degrees)	33 ± 6	33	23*	23*	25*	1**
Peak X-factor (degrees)	56 ± 4	52	54	48**	46**	46**
Peak Upper-Torso Rotation (degrees)	99 ± 6	90*	104	107*	79**	91*
Peak Pelvic Rotation (degrees)	46 ± 6	41	53*	59**	39*	49
S-Factor at Impact (degrees)	25 ± 3	21*	19**	21*	27	12**
Peak S-Factor (degrees)	48 ± 4	47	42*	50	42*	33**
O-Factor at Impact (degrees)	12 ± 3	18**	5**	3**	15	–7**
Peak O-Factor (degrees)	16 ± 4	19	13	12*	17	8 **

Note. Parameters are within 1 *SD* of professional mean, unless noted: *Between 1 and 2 *SD* of professional mean; **greater than or equal to 2 *SD* of professional mean.

(Lindsay & Horton, 2002). One case study found that a physical training program and coaching strategy designed to reduce the X-factor significantly improved low back pain (Grimshaw & Burden, 2000). This study identified Novice #1 as having an excessive X-factor during the early portion of backswing. Based on this information, recommendations for swing modification could be made to reduce X-factor, thereby minimizing low back strain and risk of injury.

In summary, this study supports the hypothesis that rotational biomechanical factors, specifically peak free moment per kilogram, peak X-factor, peak upper-torso rotation, and peak S-factor are highly consistent, highly correlated to CSI, and appear essential to golf swing power generation among professional golfers. X-factor at impact was consistent and highly correlated to CSI. The O-factor was fairly consistent and correlated with CSI, although to a lesser extent. Benchmark curves revealed individual differences in the biomechanics of amateur compared with professional golfers and may provide a basis for strategic training and injury prevention.

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