Journal of Human Kinetics volume 104/2026, 41–52 DOI: 10.5114/jhk/208353
Section I – Kinesiology

Kinematic Adaptations of Low-Handicap Golfers under Flat, Uphill, and Downhill Swing Conditions

by

Chachchanon Poolsawat [1,2], Chaipat Lawsirirat [2,]*

Golf courses often present sloped surfaces that require players to adjust their swing mechanics. Understanding these adaptations is important for optimizing performance and maintaining consistency. This research studied how low-handicap golfers adjusted their body when performing golf swings on flat, uphill, and downhill slopes. Sixteen right-handed male university golfers (mean age 21.4 ± 2.4 years; body height 177.7 ± 4.7 cm; body mass 80.4 ± 11.0 kg; handicap 3.6 ± 1.6) performed swings using a 7-iron to swing on flat (0°), uphill (+10°), and downhill (−10°) slopes. The golfers' movements were recorded using an optical motion analysis system. Kinematic data were analyzed using one-dimensional statistical parametric mapping (SPM 1D) with one-way repeated measures ANOVA. Significant differences ($p < 0.05$) were found in lower-limb joint angles and upper body inclination across slope conditions, while no significant differences were found in clubhead speed or pelvis and thorax rotation velocity. The findings show how golfers adjusted their posture to compensate for the slope while maintaining clubhead speed despite these postural changes. Initially, golfers addressed the ball by shortening the upper-side leg and aligning the upper body parallel to the slope. During the downswing, they gradually shifted their upper-body inclination toward a more upright posture relative to the ground, with lower-limb adaptations differing between the uphill and downhill conditions. These adjustments serve as strategies to sustain clubhead speed and optimize performance during uphill and downhill swings.

Keywords: *kinematics; statistical parametric mapping; golf swing*

Introduction

Performance on a slope surface needs different physiological demands and movement techniques from a flat surface in various sports, such as golf (Blenkinsop et al., 2018; Gryc et al., 2017; Hiley et al., 2021; Suzuki et al., 2021), race walking (Padulo et al., 2013), running (Damavandi et al., 2017; Vernillo et al., 2017) and alpine skiing (Seifert et al., 2017). According to Peters et al. (2015), approximately 90% of golf shots are executed on an inclined surface requiring golfers to adapt their swing mechanics to maximize their performance. Hiley et al. (2021) analyzed kinetic and kinematic data of golfers on a 5-degree slope and found that golfers with varying abilities adjusted their swing technique differently. While skilled golfers adjusted their stance to align their hips with the slope to maintain their center of pressure pattern throughout the swing (Blenkinsop et al., 2018), less skilled golfers shifted their weight onto their higher foot to maintain an upright position relative to gravity or a flat surface after the backswing phase (Hiley et al., 2021). Though swing mechanics under different slopes changed, ball speed remained unaffected by different slope conditions.

While previous studies showed the ball speed was not significantly different on inclined slopes up to 5 degrees compared to a flat surface (Blenkinsop et al., 2018; Hiley et al., 2021), the range of slopes commonly found in competitive courses can reach up to 10° (Peters et al., 2015), which potentially exceeds ankle joint

[1] *Faculty of Sport and Health Sciences, Thailand National Sports University Sukhothai Campus, Sukhothai, Thailand.*
[2] *Faculty of Sports Science, Chulalongkorn University, Bangkok, Thailand.*
* Correspondence: chaipat.l@chula.ac.th

CC BY

compensatory capabilities leading to lateral instability as seen in gait studies on 10° slopes (Damavandi et al., 2017). Hence, golfers may need to adjust their standing posture to compensate for a steeper slope (Xu et al., 2015). This kinematic adaptation may reduce the angular range of motion of the pelvis and the thorax, leading to a slower swing, lower club head speed, reduced power at impact, and, consequently, a shorter carry distance (Healy et al., 2011; Joyce, 2017; Sim et al., 2017; Takagi et al., 2019).

While swing mechanics on sloped surfaces have been widely studied, many of these studies have analyzed specific discrete events, such as address or ball impact, rather than examining the entire swing as a continuous movement. This event-based approach limits our understanding of how body segments adapt dynamically throughout the swing phase. In addition, prior research has primarily focused on changes in the center of gravity (Blenkinsop et al., 2018; Hiley et al., 2021; Li et al., 2023), without considering the continuous progression of joint kinematics and the timing of those changes. A continuous analysis of the swing can capture key adaptations that event-based approaches may miss, offering a clearer picture of how golfers respond to sloped conditions. However, no study has yet examined full-body kinematics across slope conditions throughout the entire swing using a continuous method like SPM 1D. In particular, how skilled golfers adjust their movement patterns across different slope conditions remains unclear.

The purpose of this study was to examine the influence of different slope conditions on whole-body kinematics (joint angles and velocities, along with posture changes) and club head speed throughout the swing process. One dimensional statistical parametric mapping (SPM 1D) was used to perform the statistical analysis. We hypothesized significant posture differences in proximal segments across slopes and reduced club head speed on uphill and downhill swings compared to the swing on a flat surface. The findings of this study have the potential to improve our understanding of golfer's technique for swinging on sloped surfaces and provide guidelines for golfers and coaches to perfect their swing on slope surfaces.

Methods

Participants

Sixteen right-handed male university golfers participated in the study. Their average age was 21.4 ± 2.4 years, body mass 80.36 ± 10.95 kg, body height 177.69 ± 4.66 cm, and current handicap 3.6 ± 1.6 strokes. An a priori sample size calculation was performed based on the expected effect size (f = 0.734), calculated from a partial eta squared ($p\eta^2$ = 0.35) reported in previous research on golf swing adaptations on slopes (Blenkinsop et al., 2018), with an alpha level of 0.05 and a desired statistical power of 0.80. All participants trained at least four times per week and had competed regularly in a minimum of five tournaments over the past three years. None of the participants had any significant musculoskeletal injuries during the study period. Ethics approval was granted by the Ethics Committee of Research Involving Human Research subjects, Health Science Group, Chulalongkorn University, Bangkok, Thailand (protocol code: 024/2562; approval date: 28 January 2019). Written informed consent was received from all participants prior to their participation in the study.

Data Collection

The 3D position markers on each participant were recorded using six high-speed cameras (Oqus7, Qualisys AB, Sweden) with a frame rate of 300 Hz. An artificial grass mat was placed on a custom-built plate slope to create 10º uphill and downhill slopes. Participants wore the provided tight-fitting shorts and shirt, while using their own gloves and golf shoes. After a self-selected warm-up and practicing on a custom-built plate for familiarization, body mass and height were measured. Fourteen reflective markers, each 1.6 cm in diameter, were placed bilaterally at the tip of the acromion process (AP), the anterior superior iliac spine (ASIS), the posterior superior iliac spine (PSIS), the greater trochanter (GT), the lateral femoral epicondyles (LFE), the lateral malleolus (LM), and the dorsum of the foot at the 2nd metatarsophalangeal joint (D2M) (Figure 1). Two markers were also placed on the golf club (in the middle and at the hosel), while the golf ball (Titleist ProV1x, Massachusetts, USA) was wrapped with reflective tape. Prior to data collection, participants performed a self-selected

10-min warm-up, followed by a 15-min familiarization session under all three slope conditions. They were then asked to hit 15 swings in randomized order (5 swings on each slope: flat (0°), uphill (+10°), downhill (−10°)) using the provided 7-iron club (TaylorMade RAC TP Forged, Illinois, USA). They were instructed to hit vigorously and accurately into a net positioned exactly 3 m away. Before each swing, the ball was placed precisely at the marked position to ensure consistency.

Data Processing

The paper adopted the five key events in the golf swing (Ball and Best, 2007): (1) address (AD), the first backward movement of the club; (2) mid backswing (MB), when the club shaft is parallel to the horizontal plane; (3) top of the backswing (TB), the instant just before the shaft begins its downswing; (4) mid downswing (MD), when the club shaft is again parallel to the horizontal plane; and (5) ball impact (BI), the moment the club makes contact with the ball. These events were coded and detected using a Matlab (R2021b, MathWorks, Natick, MA) script. They were further used to define swing phases: the early backswing (AD–MB), the late backswing (MB–TB), the early downswing (TB–MD), and the late downswing (MD–BI). The Qualisys Motion Capture System and its software (Qualisys, Gothenburg, Sweden) were used to collect marker data, and the software reported club head speed as well as bilateral hip, knee, and ankle flexion angles from address (AD) to ball impact (BI). A Matlab code was written to calculate the angles of X-factor, an inclination angle of the pelvis and the thorax, and the rotational velocity of the pelvis and the thorax. All kinematic variables were smoothed using a fourth-order, low pass Butterworth filter at 10 Hz for kinematic variables and 25 Hz for club head speed (Takagi et al., 2019). A swing with fastest club head speed for each participant under each condition at BI was selected for statistical analysis to allow better understanding of the mechanics of peak performance under given conditions.

Calculations of the Pelvis and the Thorax Inclination Angle and the X-factor

The pelvis and thorax local right-handed coordinate systems (LCS) were established based on anatomical landmarks (Figure 1). The pelvis LCS was defined with its origin at the midpoint between the anterior superior iliac spines (ASIS). The X-axis (X_P) extended toward the right ASIS, the Z-axis (Z_P) was perpendicular to the pelvis plane formed by the ASIS and the pelvis origin, and the Y-axis (Y_P) was defined as the cross-product of X_P and Z_P. The thorax LCS was defined with the same origin as the pelvis. The Z-axis (Z_t) pointed towards the midpoint between acromion processes, the Y-axis (Y_t) was perpendicular to the thorax plane formed by the acromion processes, and the X-axis (X_t) was the cross-product of Y_t and Z_t (Brown et al., 2013; Robertson et al., 2013).

In this study, a Z-Y-X Euler sequence was used to calculate pelvis and thorax orientations. Using the notation $C_a = \cos\theta_a$ and $S_a = \sin\theta_a$ for a = x, y, z and $\theta = \alpha,\ \beta,\ \gamma$ this sequence was formally expressed in a matrix form as seen in Equation (1):

$$[R_{zyx}] = \begin{bmatrix} r_{00} & r_{01} & r_{02} \\ r_{10} & r_{11} & r_{12} \\ r_{20} & r_{21} & r_{22} \end{bmatrix} = \begin{bmatrix} C_yC_z & C_zS_xS_y - C_xS_z & C_xC_zS_y + S_xS_z \\ C_yS_z & C_xC_z + S_xS_yS_z & -C_zS_x + C_xS_yS_z \\ -S_y & C_yS_x & C_xC_y \end{bmatrix} \quad (1)$$

Pelvis and thorax inclination angles were defined as the elevation differences between the left and right sides, calculated by determining the orientation of the pelvis and thorax local coordinate system (LCS) relative to the global coordinate system (GCS) on the Y-axis. The pelvis inclination angle was calculated using Equations (2) and (3):

$$[R_{zyx}^{PO}] = [O_{GCS}][P_{LCS}]^T \quad (2)$$

$$\alpha_y = asin(-r_{20}) \qquad (-\pi/2 < \alpha_y < \pi/2) \quad (3)$$

where $[R_{zyx}^{PO}]$ was the rotation matrix of the pelvis LCS relative to the GCS,
$[P_{LCS}]$ was the matrix of the pelvis LCS,
$[O_{GCS}]$ was the matrix of the GCS,
r_{20} was the element (2,0) of the rotation matrix $[R_{zyx}^{PO}]$,
α_y was the pelvis inclination angle.

A similar technique was applied to find thorax inclination (β_y) where the matrix pelvis LCS $[P_{LCS}]$ was replaced by the matrix thorax LCS $[T_{LCS}]$ in order to calculate the rotation matrix of the thorax LCS relative to the GCS $[R_{zyx}^{TO}]$ using Equation (2), with r_{20} being the element of the

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

matrix $[R_{zyx}^{TO}]$ in Equation (3).

The X-factor was determined as the separation angle between the thorax and the pelvis by calculating the thorax LCS orientation relative to the pelvis LCS. The first rotation around the Z-axis represented the X-factor, which was calculated using Equations (4) and (5):

$$[R_{zyx}^{TP}] = [P_{LCS}][T_{LCS}]^T \quad (4)$$

$$\gamma_z = atan2(-r_{01}, r_{00}) \quad (-\pi/2 < \gamma_y < \pi/2) \quad (5)$$

where $[R_{zyx}^{TP}]$ was the rotation matrix of the thorax LCS relative to the pelvis LCS,
r_{01}, r_{00} were elements (0,1) and (0,0) of the rotation matrix $[R_{zyx}^{TP}]$,
γ_z was the X-factor.

Calculations of the Pelvis and Thorax Rotation Velocities

Pelvis and thorax rotation velocities were calculated as the rate of change of their respective rotation angles over time. Specifically, the rotational velocity was determined using Equations (6)–(8).

$$[R_{zyx}^{P^tP^{t-1}}] = [P_{LCS}^{t-1}][P_{LCS}^{t}]^T \quad (6)$$

$$\alpha_z = atan2(-r_{01}, r_{00}) \quad (-\pi/2 < \alpha_y < \pi/2) \quad (7)$$

$$\dot{\alpha}_z = \alpha_z * f \quad (8)$$

where $[R_{zyx}^{P^tP^{t-1}}]$ was the rotation matrix of the pelvis LCS at time *t* relative to the prior pelvis LCS at time *t-1*,
$[P_{LCS}^{t-1}]$ was the matrix of the pelvis LCS at time *t-1*,
$[P_{LCS}^{t}]$ was the matrix of the pelvis LCS at time *t*,
r_{01}, r_{00} were elements of the rotation matrix $[R_{zyx}^{P^tP^{t-1}}]$,
f was the frame rate of data collection (300 Hz),
α_z was the pelvis rotation angle,
$\dot{\alpha}_z$ was pelvis rotation velocity.

Similarly, the thorax rotation velocity ($\dot{\beta}_z$) was found by replacing the matrix pelvis LCS $[P_{LCS}^{t-1}]$ and $[P_{LCS}^{t}]$ with the matrix thorax LCS $[T_{LCS}^{t-1}]$ and $[T_{LCS}^{t}]$, respectively. Equation (8) was used to determine the thorax rotation velocity.

Positive values were used to express the ankle, knee, and hip flexion. The pelvis and thorax inclination angles were positive when the participant inclined these segments in the counterclockwise direction and the rotation velocity was positive when the pelvis or the thorax rotated towards the target.

Statistical Analysis

The variables used in the analysis were bilateral ankle flexion angles, knee flexion angles, hip flexion angles, pelvis and thorax inclination angles, the X-factor, pelvis and thorax rotation velocities, and club head speed. The continuous data of all variables and five key events from AD to BI were normalized to 101 nodes (0–100% of the swing) and were averaged for each swing condition (flat, uphill, and downhill).

A one-way repeated measures analysis of variance (ANOVA) was performed through one dimensional statistical parametric mapping (SPM 1D) using the open source spm1d code (v.M0.1, www.spm1d.org) in MATLAB (De Ridder et al., 2013; Morais et al., 2023). When statistical significance was found, post hoc *t*-tests with a Bonferroni adjustment were performed. The significance level was set at $\alpha = 0.05$. This approach enabled a more detailed examination of how golfers adapted their movements throughout the entire motion and allowed for the identification of the precise phases where significant differences occurred (Brunetti et al., 2024; Pataky, 2012; Sinclair et al., 2018).

Partial eta squared ($p\eta^2$) was calculated to report effect sizes and interpreted as small (0.01), medium (0.06), or large (0.14) (Richardson, 2011). To assess within-subject consistency of swing performance, intraclass correlation coefficients (ICCs) were calculated for club head speed at BI using five swing trials per slope condition collected during data acquisition, with values interpreted as poor (<0.50), moderate (0.50–0.75), good (0.75–0.90), or excellent (>0.90) reliability (Koo & Li, 2016). This approach provided estimates of swing consistency under each condition.

Results

The golf swing was divided into four phases for analysis: phase 1 (early backswing, 0%–44%), phase 2 (late backswing, 44%–77%), phase 3 (early downswing, 77%–94%), and phase 4 (late downswing, 94%–100%) (Table 1). These phase numbers were used throughout the results and the discussion section for clarity. For all tested variables, partial ($p\eta^2$) values ranged from 0.25 to 0.34, representing large effects. The ICCs for

club head speed at BI were 0.89 for the flat surface, 0.67 for the uphill slope, and 0.85 for the downhill slope. These values indicated moderate to good within-subject consistency, supporting the use of the fastest trial as a reliable representation of swing performance. Based on the ANOVA results, significant differences were found throughout the entire swing in left ankle flexion and left knee flexion, whereas left hip flexion differed only during phase 1. For the right side, significant differences were observed in right ankle flexion across the entire swing, right knee flexion from phase 2 to phase 3, and right hip flexion during most of phases 3 and 4. Additionally, pelvis inclination showed significant differences throughout the entire swing, while thorax inclination differed only during phases 1, 3, and 4. Key statistical results are summarized in Table 1.

Figure 2 (1A–1C) shows that no significant differences were found in pelvis and thorax rotational velocities or club head speed across the three slope conditions throughout the entire swing.

In contrast, Figure 2 (2D–2F) shows that pelvis and thorax inclination angles and the X-factor angles were significantly different among the three conditions. The inclination angles of both the pelvis and the thorax were significantly higher during the uphill swing, followed by the flat surface swing, and lowest during the downhill swing. Additionally, the X-factor was significantly higher in the uphill swing compared to the downhill swing during phase 1.

Table 1. Significant results of ANOVA and post-hoc analysis using SPM on swing kinematics.

		SPM-pairwise comparison			
Variables	SPM-ANOVA Range (p-value)	Flat vs Uphill Range (p-value)	Flat vs Downhill Range (p-value)	Uphill vs Downhill Range (p-value)	$p\eta^2$
Left ankle flexion (°)	0–100% ($p < 0.001$)	0–87.7% ($p < 0.001$)#	NS	0–100% ($p < 0.001$)#	0.27
Left knee flexion (°)	0–100% ($p < 0.001$)	0–100% ($p < 0.001$)#	NS	0–100% ($p < 0.001$)#	0.25
Left hip flexion (°)	0–40.4% ($p < 0.005$)	NS	NS	0–40.7% ($p < 0.003$)#	0.26
Right ankle flexion (°)	0–100% ($p < 0.001$)	NS	53.9–100% ($p < 0.001$)&	0–100% ($p < 0.001$)&	0.26
Right knee flexion (°)	38.7–88.5% ($p < 0.001$)	NS	51.1–84.5% ($p = 0.002$)&	43.1–88.3% ($p < 0.001$)&	0.27
Right hip flexion (°)	78.3–100% ($p < 0.018$)	NS	80.5–100% ($p = 0.005$)&	79.3–100% ($p = 0.002$)&	0.28
Pelvis inclination angles (°)	0–100% ($p < 0.001$)	0–49.5% ($p < 0.001$)#	0–79.5% ($p < 0.001$)$	0–98.4% ($p < 0.001$)#	0.27
Thorax inclination angles (°)	0–43.9% ($p < 0.001$) 88–99% ($p = 0.023$)	0–23.4% ($p < 0.001$)#	0–24.5% ($p < 0.001$)$	0–52.5% ($p < 0.001$)# 91–97% ($p < 0.001$)#	0.32
X-factor (°)	0–19.7% ($p < 0.010$)	NS	NS	0–19.5% ($p = 0.001$)#	0.29
Pelvis rotation velocity (°/s)	NS	NS	NS	NS	0.33
Thorax rotation velocity (°/s)	NS	NS	NS	NS	0.32
Club head speed (m/s)	NS	NS	NS	NS	0.34

0–44% : early backswing (Phase 1); 44–77% : late backswing (Phase 2); 77–94% : early downswing (Phase 3); 94–100% : late downswing (Phase 4); $: Flat presented higher values; # : Uphill presented higher values; & : Downhill presented higher values; NS: not significant

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

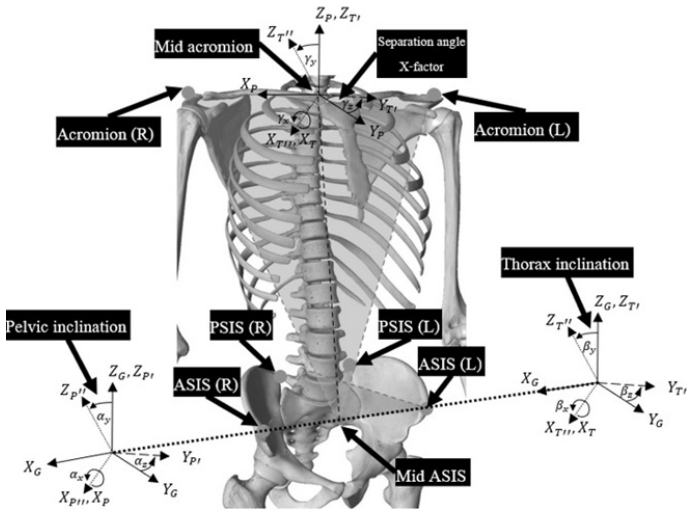

Figure 1. Definition of the pelvis LCS and the thorax LCS along with the GCS.

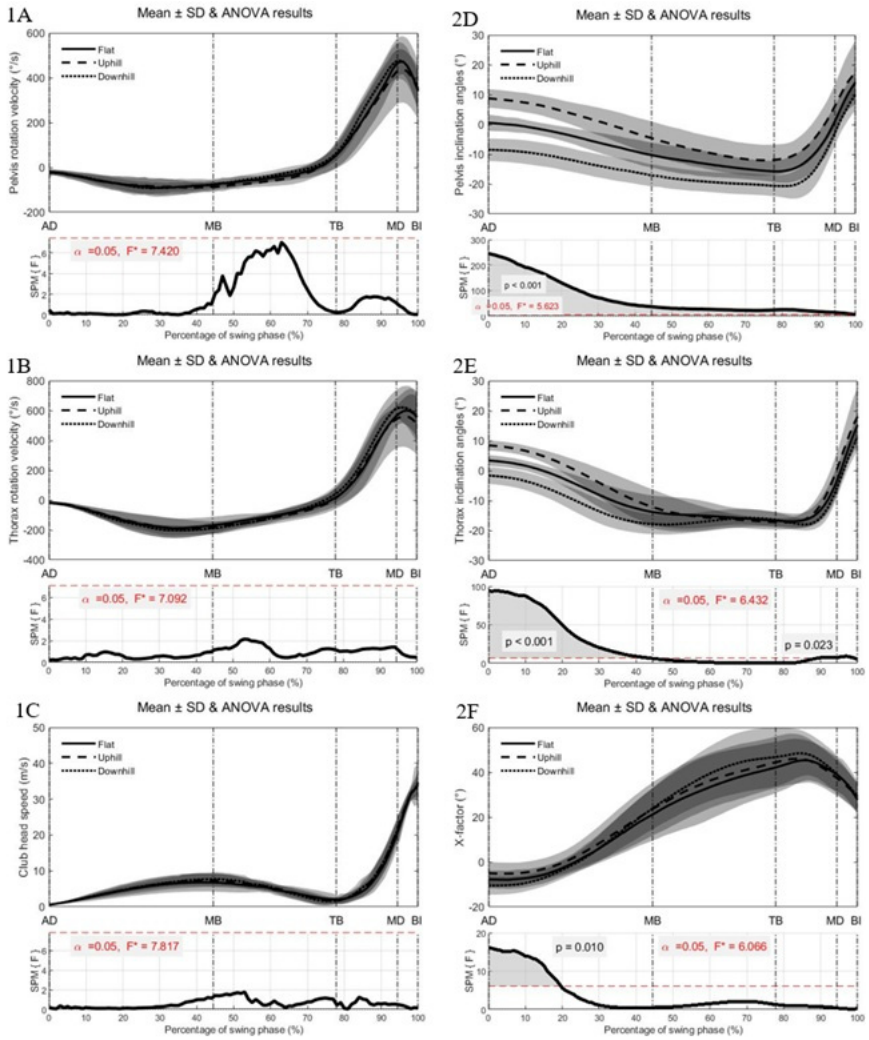

Figure 2. Differences in kinematic variables and clubhead speed across slope conditions. Panel 1: Pelvis rotation velocity (1A), thorax rotation velocity (1B), and clubhead speed (1C). Panel 2: Pelvis inclination (2D), thorax inclination (2E), and X-factor (2F). Upper graphs show mean ± SD for flat (solid), uphill (dashed), and downhill (dotted) swings. Lower graphs show SPM{F} statistics with significant intervals marked ($p < 0.05$).

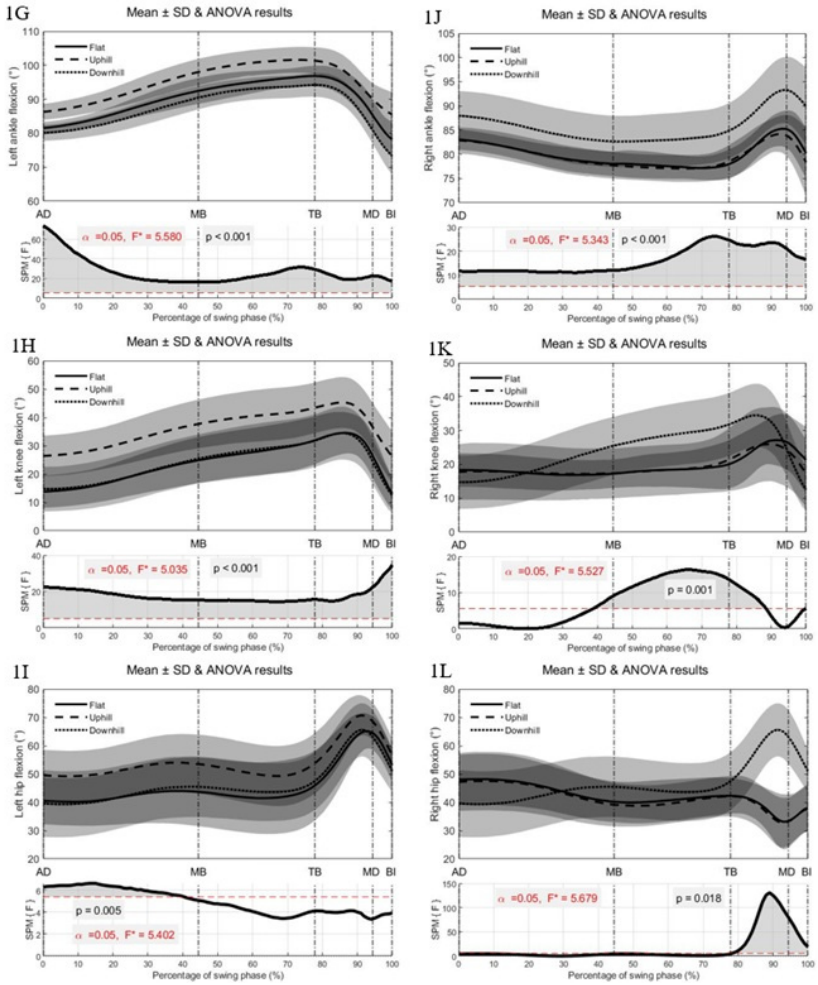

Figure 3. Differences in lower-limb joint flexion angles across slope conditions. Panel 1: Left ankle (1G), knee (1H), and hip (1I) flexion. Panel 2: Right ankle (2J), knee (2K), and hip (2L) flexion. Upper graphs show mean ± SD for flat (solid), uphill (dashed), and downhill (dotted) swings. Lower graphs show SPM{F} statistics with significant intervals marked ($p < 0.05$).

Figure 3 (1G–1I) illustrates the pairwise comparisons of left-side flexion angles across different slope conditions. The ankle flexion angle during the uphill swing was significantly greater than that of the downhill swing throughout the entire swing and significantly greater than the flat-surface swing from phase 1 to phase 3. For knee flexion, the uphill swing showed significantly greater angles than both the flat and downhill swings across the entire swing. Regarding hip flexion, the uphill swing displayed significantly greater angles than the downhill swing during most of phase 1.

The pairwise comparisons of right-side flexion angles across different slope conditions are presented in Figure 2 (2J–2L). The ankle flexion angle of the downhill swing was significantly higher than that of the uphill swing over the entire swing, but was significantly higher than the swing performed on the flat surface from the mid of phase 3 to BI. The knee flexion angle of the downhill swing was significantly higher than the

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

knee flexion angle when performed on the flat and uphill surfaces from the mid of the swing. Lastly, the hip flexion angle of the downhill swing was significantly higher than that of the flat and uphill swings from the middle of phase 3 to the ball impact.

Discussion

This study aimed to compare the kinematic differences in golf swings performed by low-handicap golfers on flat, uphill, and downhill slopes of 10 degrees. SPM analysis was conducted to comprehensively understand the kinematic adaptations over the entire swing to varying slope conditions.

Contrary to our hypothesis, no significant differences in club head speed or pelvis and thorax rotation velocities were observed across the three slope conditions, which is consistent with the findings of Hiley et al. (2021) on a 5° slope. Moreover, the patterns and magnitude of pelvis and thorax rotation velocities in this study also agreed with the results from Horan and Kavanagh (2012). Though there were no significant differences in rotation velocities of the thorax, the pelvis and the club head speed, our results revealed significant differences in lower extremity flexion angles across multiple joints, including the ankles, knees, and hips. These adaptations reflected the need to maintain balance and control the body position under varying slope conditions. Golfers dynamically adjusted their inclination angles to limit unnecessary vertical movements, thereby preserving stability and swing efficiency. Such dynamic management of vertical momentum is crucial, as excessive vertical momentum can negatively affect performance efficiency and stability, a finding similarly reported in other sports contexts (Ozaki and Ueda, 2024). Specifically, golfers aligned the upper body (both their pelvis and thorax inclination) at AD to be parallel to the slope they were standing on. This adjustment provided stability and balance at the beginning of the swing. By the end of the swing, pelvis and thorax inclination became similar to that observed during the flat-surface swings. As a result, golfers were able to maintain consistent pelvis and thorax rotation mechanics regardless of slope conditions contributing to preserving club head speed.

Uphill Condition

Our results showed that golfers adjusted their lower limb differently under different slopes. The ankle and knee flexion angles on the upper side of the slope were significantly greater than those observed in the swing on a flat surface throughout most of the swing phases. However, no significant differences were observed on the lower side. These adaptations helped golfers maintain lateral upper body movement toward the uphill side, preventing the center of mass from shifting outside the base of support and maintaining balance during the swing (Hume et al., 2005). These findings align with side-slope running studies, where greater ankle and knee flexion on the higher side prevented lateral instability (Damavandi et al., 2017). In addition, the motion pattern resembled that observed by Faux et al. (2019) who found similar lower extremity kinematics of the golf swing. The observed changes in lower-limb joint mechanics likely enable golfers to avoid an excessive pelvic tilt or unwanted movement, potentially reducing injury risk and promoting optimal performance—an interpretation supported by similar findings regarding the pelvic tilt and injury prevention in elite sprinters (Hegyi et al., 2025).

The pelvis and thorax inclination angles exhibited higher values compared to the flat condition during phase 1. This suggests that golfers initially inclined their upper body parallel to the slope. However, as the backswing progressed, these differences diminished until no significant differences in inclination angles of the pelvis and the thorax were found in the downswing phase. The adjustments suggest that golfers adapt their posture throughout the swing rather than maintaining a perpendicular position relative to the surface as proposed by Hiley et al. (2021). Adjusting thorax inclination relative to gravity was likely to reduce the transverse shoulder angle, which effectively decreased the ball launch angle (Zhang & Shan, 2014) and counteracted the increased launch angle associated with uphill swings (Blenkinsop et al., 2018; Hiley et al., 2021).

Our results showed that the X-factor of the uphill swing was not significantly different from the flat-surface swing even though participants adjusted their standing. This suggests that skilled golfers can adjust their stance mechanics without

compromising rotational performance. Similarly, Stastny et al. (2015) found that golfers with a single lower-limb amputation maintained fluent swing kinematics and low movement variability. The X-factor results demonstrated golfers' ability to maintain the movement pattern and achieve sufficient maximum separation to trigger the stretch-shortening cycle, facilitating power generation and producing club head speed (Horan et al., 2010). This finding was further supported by the pelvis and thorax rotation velocity, as well as the club head speed results, which showed that all demonstrated movement patterns and magnitude comparable to those observed in swings on flat surfaces.

Downhill Condition

The ankle and knee flexion angles on the lower side of the slope showed no significant differences compared to flat surfaces. However, the upper side exhibited significantly greater ankle and knee flexion from phase 2 to the ball impact. These adaptations were similar to the uphill swing but happened on the opposite side helping golfers maintain their standing balance and control their body during the swing. However, the hip flexion angles of the upper side hip flexion increased during phase 3 instead of decreasing as seen in flat and uphill swings (Faux et al., 2019). As the ankle and knee flexion angles on the upper side increased due to the elevated ground, the ability to sufficiently lower the right knee during the downswing became restricted. Therefore, golfers needed to increase hip flexion on the upper side during phase 3 to compensate for the downhill slope.

The pelvis and thorax inclination results in downhill swings followed the same trend as those in uphill swings. Golfers initially inclined their upper body in the direction of the slope during phase 1. As the swing progressed, the inclination angles gradually changed to be similar to those performed under the flat condition. This adaptation suggests that golfers dynamically adjusted their inclination rather than maintained a fixed orientation relative to the ground, highlighting the importance of achieving a flat swing posture to facilitate consistent rotational mechanics and club head control (Horan et al., 2010).

Limitations

This study has some limitations that should be acknowledged. First, the study focused primarily on kinematic analysis. By considering only kinematics, we were able to offer rich and detailed insights into movement patterns that require careful and thorough investigation. In particular, our study applied statistical parametric mapping (SPM) to analyze the entire swing path, rather than focusing on discrete events. The study allowed us to capture a more continuous and informative view of the golfer's movement and gain better understanding of the swing under different slope conditions. Second, the study was conducted on grass surfaces with a 10-degree slope angle. Different adaptations may occur on other surface types and steeper slopes. Finally, this study focused on analyzing the fastest trial for each golfer to capture peak performance and biomechanical efficiency. While this approach does not present intra-golfer variability across all kinematic variables, the ICC calculated from five trials per condition showed high consistency in peak club head speed, supporting the use of the fastest trial as a valid representation of swing performance. Given that all participants were low-handicap golfers (0–9), their swings were likely executed with high precision and consistency. Future studies should consider incorporating kinetic measurements along with multiple trials per participant to provide a more comprehensive understanding of golfers' adaptation strategies and performance outcomes under varying slope conditions.

Conclusions

This study demonstrated that low-handicap golfers adapted their swings on 10° uphill and downhill slopes by adjusting lower limb flexion angles and adapting pelvis and thorax inclination. For the uphill swing, skilled golfers exhibited greater ankle and knee flexion on the upper side to maintain stability, while their pelvis and thorax inclined in the direction of the slope before gradually returning to a flat-swing alignment. When playing on downhill slopes, a similar adaptation in the upper-side lower limb was observed. However, hip flexion showed an opposite pattern, increasing during phase 2 to compensate for the limited ankle and knee flexion and to help maintain precision at impact, with the

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

upper body again adjusting to the slope before realigning to a flat-swing alignment to preserve rotational mechanics and club head speed. The results did not indicate any restrictions in upper body mechanics. Instead, adjustments were observed primarily in the lower extremity, while rotational movement and club head speed were maintained despite the slope up to 10°. These findings emphasize the importance of slope-specific adjustments to swing mechanics, providing insights for golfers and coaches to optimize performance on sloped terrains. Based on these findings, golfers and coaches may benefit from practicing on sloped surfaces, with an emphasis on adapting postural alignment and adjusting lower-limb mechanics, particularly on the higher side of the slope. Such training may help maintain swing efficiency under different terrain conditions.

Author Contributions: Conceptualization: C.P. and C.L.; methodology: C.P. and C.L.; software: C.P.; validation: C.P. and C.L.; formal analysis: C.P. and C.L.; investigation: C.P.; resources: C.P. and C.L.; data curation: C.P.; writing—original draft preparation: C.P.; writing—review & editing: C.P. and C.L.; visualization: C.P.; supervision: C.L.; project administration: C.P.; funding acquisition: C.L. Both authors have read and agreed to the published version of the manuscript.

ORCID iD:

Chachchanon Poolsawat: https://orcid.org/0009-0006-8886-2781

Chaipat Lawsirirat: https://orcid.org/0000-0002-0331-5003

Funding Information: This research was funded by the Faculty of Sports Science at the Chulalongkorn University, Bangkok, Thailand.

Institutional Review Board Statement: This study was conducted following the principles of the Declaration of Helsinki, and approved by the Ethics Committee of Research Involving Human Research subjects, Health Science Group, Chulalongkorn University, Bangkok, Thailand (protocol code: 024/2562; approval date: 28 January 2019).

Informed Consent: Informed consent was obtained from all participants included in the study.

Conflicts of Interest: The authors declare no conflict of interest.

Acknowledgements: The authors express sincere gratitude to the golf players who participated, and to the Faculty of Sports Science at the Chulalongkorn University, Bangkok, Thailand, for making this study possible.

Received: 14 March 2025

Accepted: 17 July 2025

References

Ball, K., & Best, R. (2007). Different centre of pressure patterns within the golf stroke I: Cluster analysis. *Journal of Sports Sciences*, *25*(7), 757–770.

Blenkinsop, G. M., Liang, Y., Gallimore, N. J., & Hiley, M. J. (2018). The effect of uphill and downhill slopes on weight transfer, alignment, and shot outcome in golf. *Journal of Applied Biomechanics*, *34*(5), 361–368.

Brown, S. J., Selbie, W. S., & Wallace, E. S. (2013). The X-Factor: An evaluation of common methods used to analyse major inter-segment kinematics during the golf swing. *Journal of Sports Sciences*, *31*(11), 1156–1163.

Brunetti, C., Rabello, R., Poletti, N., Bertozzi, F., & Sforza, C. (2024). Statistical Parametric Mapping to detect the effects of the secondary jump direction on landing kinematics. *Sports Biomechanics*. Advance online publication. https://doi.org/10.1080/14763141.2024.2354422

Damavandi, M., Eslami, M., & Pearsall, D. J. (2017). Side-sloped surfaces substantially affect lower limb running kinematics. *Sports Biomechanics*, *16*(1), 1–12.

De Ridder, R., Willems, T., Vanrenterghem, J., Robinson, M., Pataky, T., & Roosen, P. (2013). Gait kinematics of subjects with ankle instability using a multisegmented foot model. *Medicine and Science in Sports and Exercise*, *45*(11), 2129–2136.

Faux, L., Carlisle, A., Vickers, J., & Diss, C. (2019). The effect of alterations in foot centre of pressure on lower body kinematics during the five-iron golf swing. *Journal of Sports Sciences*, *37*(17), 2014-2020.

Gryc, T., Stastny, P., Zahálka, F., Smółka, W., Żmijewski, P., Gołaś, A., Zawartka, M., & Malý, T. (2017). Performance and kinematic differences in putting between healthy and disabled elite golfers. *Journal of Human Kinetics*, *60*(1), 233–241. https://doi.org/10.1515/hukin-2017-0113

Healy, A., Moran, K. A., Dickson, J., Hurley, C., Smeaton, A. F., O'Connor, N. E., Kelly, P., Haahr, M., & Chockalingam, N. (2011). Analysis of the 5 iron golf swing when hitting for maximum distance. *Journal of Sports Sciences, 29*(10), 1079–1088.

Hegyi, A., Sarcher, A., Varenne, F., Mornet, A., Cadu, J., Carcreff, L., Lacourpaille, L. (2025). Validating Field Methods to Estimate the Pelvic Tilt in Sprinting and the Relationship between Prior Hamstring Injury and the Pelvic Tilt in Elite Female Soccer Players. *Journal of Human Kinetics*, *98*, 17–28. https://doi.org/10.5114/jhk/194851

Hiley, M. J., Bajwa, Z., Liang, Y., & Blenkinsop, G. M. (2021). The effect of uphill and downhill slopes on centre of pressure movement, alignment and shot outcome in mid-handicap golfers. *Sports Biomechanics*, *20*(7), 781–797.

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*(8), 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*(2), 165–174.

Hume, P. A., Keogh, J., & Reid, D. (2005). The role of biomechanics in maximising distance and accuracy of golf shots. *Sports Medicine*, *35*(5), 429–449.

Joyce, C. (2017). An examination of the correlation amongst trunk flexibility, x-factor and clubhead speed in skilled golfers. *Journal of Sports Sciences*, *35*(20), 2035–2041.

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine*, *15*(2), 155–163.

Li, B., Li, H., Tang, X., Hu, Z., Wu, C., Kim, Y., & Kim, S. (2023). Effect of slope change on kinematics of amateur golfers' full swing. *Technology and Health Care*, *31*(1_suppl), 271–282.

Morais, J. E., Barbosa, T. M., Lopes, T., Gourgoulis, V., Nikodelis, T., & Marinho, D. A. (2023). Analysis of upper limb propulsion in young swimmers in front-crawl through Statistical Parametric Mapping. *Journal of Biomechanics*, *159*, 111792.

Ozaki, Y., & Ueda, T. (2024). The Relationship between Take-Off Parameters and Relative Vertical Momentum of Free Limbs at the Take-Off in Hurdle Clearance. *Journal of Human Kinetics*, *93*, 41–52. https://doi.org/10.5114/jhk/176106

Padulo, J., Annino, G., D'Ottavio, S., Vernillo, G., Smith, L., Migliaccio, G. M., & Tihanyi, J. (2013). Footstep analysis at different slopes and speeds in Elite race walking. *Journal of Strength & Conditioning Research*, *27*(1), 125–129.

Pataky, T. C. (2012). One-dimensional statistical parametric mapping in Python. *Computer Methods in Biomechanics and Biomedical Engineering*, *15*(3), 295–301.

Peters, R., Smith, N., & Lauder, M. (2015). Quantifying the gradients exposed to a professional golfer during a round of golf. *In F. Colloud, M. Domalain, & T. Monnet (Eds.), Proceedings of the 33rd International Conference on Biomechanics in Sports* (pp. 1153–1156). Poitiers, France.

Richardson, J. T. (2011). Eta squared and partial eta squared as measures of effect size in educational research. *Educational Research Review*, *6*(2), 135–147.

Robertson, D. G. E., Caldwell, G. E., Hamill, J., Kamen, G., & Whittlesey, S. (2013). *Research Methods in Biomechanics*. Human kinetics.

Articles published in the Journal of Human Kinetics are licensed under an open access Creative Commons CC BY 4.0 license.

Seifert, J., Stöggl, T., Scheiber, P., Heizinger, E., & Müller, E. (2017). Grade and speed have greater influence on HR and RPE than ability, sex, and age in alpine skiing. *Journal of Sports Sciences*, *35*(5), 419–425.

Sim, T., Yoo, H., Choi, A., Lee, K. Y., Choi, M.-T., Lee, S., & Mun, J. H. (2017). Analysis of pelvis-thorax coordination patterns of professional and amateur golfers during golf swing. *Journal of Motor Behavior*, *49*(6), 668–674.

Sinclair, J., Butters, B., & Stainton, P. (2018). Acute effects of barefoot and minimalist footwear on medial tibiofemoral compartment loading during running: A statistical parametric mapping approach. *Journal of Human Kinetics*, *65*(1), 35–44. https://doi.org/10.2478/hukin-2018-0037.

Stastny, P., Maszczyk, A., Tománková, K., Kubový, P., Richtrová, M., Otáhal, J., Čichoň, R., Mostowik, A., Żmijewski, P., & Cięszczyk, P. (2015). Kinetic and kinematic differences in a golf swing in one and both lower limb amputees. *Journal of Human Kinetics*, *48*(1), 33–41. https://doi.org/10.1515/hukin-2015-0089.

Suzuki, T., Sheahan, J. P., Miyazawa, T., Okuda, I., & Ichikawa, D. (2021). Comparison of TrackMan data between professional and amateur golfers at swinging to uphill and downhill fairways. *Open Sports Sciences Journal*, *14*(1). 137–143. https://doi.org/10.2174/1875399X02114010137

Takagi, T., Murata, M., Yokozawa, T., & Shiraki, H. (2019). Dynamics of pelvis rotation about its longitudinal axis during the golf swing. *Sports Biomechanics*, *20*(5), 583–602. https://doi.org/10.1080/14763141.2019.1585472

Vernillo, G., Giandolini, M., Edwards, W. B., Morin, J.-B., Samozino, P., Horvais, N., & Millet, G. Y. (2017). Biomechanics and physiology of uphill and downhill running. *Sports Medicine*, *47*, 615–629.

Xu, H., Wang, Y., Greenland, K., Bloswick, D., & Merryweather, A. (2015). The influence of deformation height on estimating the center of pressure during level and cross-slope walking on sand. *Gait & Posture*, *42*(2), 110–115.

Zhang, X., & Shan, G. (2014). Where do golf driver swings go wrong? Factors influencing driver swing consistency. *Scandinavian Journal of Medicine & Science in Sports*, *24*(5), 749–757.