Small changes in ball position at address cause a chain effect in golf swing

Sung Eun Kim1,2, Jangyun Lee3,4, Sae Yong Lee1,5, Hae-Dong Lee1,2, Jae Kun Shim6,7,8,9,10 & Sung-Cheol Lee1,2*

The purpose of this study was to investigate how the ball position along the mediolateral (M-L) direction of a golfer causes a chain effect in the ground reaction force, body segment and joint angles, and whole-body centre of mass during the golf swing. Twenty professional golfers were asked to complete five straight shots for each 5 different ball positions along M-L: 4.27 cm (ball diameter), 2.14 cm (ball radius), 0 cm (reference position at preferred ball position), –2.14 cm, and –4.27 cm, while their ground reaction force and body segment motions were captured. The dependent variables were calculated at 14 swing events from address to impact, and the differences between the ball positions were evaluated using Statistical Parametric Mapping. The left-sided ball positions at address showed a greater weight distribution on the left foot with a more open shoulder angle compared to the reference ball position, whereas the trend was reversed for the right-sided ball positions. These trends disappeared during the backswing and reappeared during the downswing. The whole-body centre of mass was also located towards the target for the left-sided ball positions throughout the golf swing compared to the reference ball position, whereas the trend was reversed for the right-sided ball positions. We have concluded that initial ball position at address can cause a series of chain effects throughout the golf swing.

Biomechanics of golf swing has been a popular topic of research in the field of sport science not only because it is directly applicable to the golfer’s performance, but also because it can be used as a window to the underlying mechanisms of human movements realised through the parallel and serial connections of body segments. One of the main goals of golf swing is to maximise the club-head speed and accuracy, while taking advantage of force transfer through the kinematic chain of the body segments. A large number of existing studies on golf swing has helped identify the kinematic and kinetic variables that are important for golf swing performance such as trunk rotation, lower body flexion, and centre of mass/pressure movement, which have revealed important underlying mechanisms of golf swing in relation to its control. However, our knowledge regarding how the initial state of the control system, such as the address position, influences the swing behaviour is largely limited. Due to the linked segments of the whole body used in golf swing, a small change in the address position can easily result in a chain effect, serial events caused by an initial state, through the course of backswing and downswing followed by the address.

One of the important initial states in golf is the ball position relative to the golfer. Many golf coaches believe that the address position influences the entire golf swing causing a chain effect through the course of golf swing and eventually changes the outcome, a golf shot that eventually determines the distance, accuracy, and consistency. This is why coaches spend many hours on the address position of golfers to change and improve golf swing and shot. "If they (golfers) are set incorrectly in posture, they can't work the body correctly... they're moving the wrong plane of movement, and then part of the reason why their club is moving in a funny fashion is because the body is actually moving incorrectly," stated one coach. Another coach stated, "An incorrect posture at setup..."
could have detrimental effects on the remainder of the swing. Any compensatory movement or counterbalances in the golf swing were results of poor posture. These coaches clearly understand that there is a chain effect in golf swing, which is influenced by the initial state at address.

Kim et al. studied the effect of the ball position along the mediolateral (M-L) direction, and found that the left-sided ball position causes open shoulder alignment at address as well as changes in club-head movement at impact. Another study by Bradshaw et al. investigated golfers with different handicap levels and found that the variability of the M-L ball position is related to the variability of the club velocity at impact. Similarly, Zhang et al. found that the variability of the M-L ball position is related to the variability of the ball launch angle after impact. Although these studies have revealed the importance of the ball position regarding the initial setup and final outcomes of golf swing, our knowledge on the influence of M-L ball position on the golfer’s movements during the course of golf swing is largely limited. A comprehensive study on the ball position and golf swing can potentially offer an opportunity to better understand the influences of the initial state on the consequences of swing behaviour. Furthermore, the outcomes of such a study can provide golf coaches and players with the knowledge of golf swing mechanisms in relation to the ball position and the insights into the improvement of coaching strategies, and eventually, golfer’s performance. For example, if a golf ball curves dramatically in flight from left to right for right-handed golfers (called ‘slice’ in golf), golf coaches and players often attribute it to insufficient shoulder rotation, whereas a mal-positioned golf ball may be the cause of a chain effect: an open shoulder alignment leading to insufficient shoulder rotation, and eventually, slice.

Contrary to other previous studies that focused more on the influence of M-L ball position on address position, club-head velocity at impact, and ball trajectory after impact, the current study investigates the behaviour of the golfer during the course of golf swing between address and impact. Our study examines the influence of the M-L ball position on the kinetic and kinematic variables considered to be critical in golf swing mechanism, such as ground reaction force (GRF), centre of pressure (COP), body segment and joint angles, and whole-body centre of mass (COM), during swing. We hypothesise that a small change in ball position in the M-L direction at address will cause a chain effect through the course of the golf swing.

Methods

Participants. Twenty professional male golfers (mean ± standard deviation: age: 29.25 ± 4.20 years, height: 1.78 ± 0.06 m, mass: 77.96 ± 10.48 kg) volunteered to participate in this study. The participants had no history of chronic pain, major injuries, or surgery in at least the last 6 months. All procedures were approved and performed in accordance with the ethical standards of the Yonsei University institutional review board (IRB#1040917-201601-SB-104-02). Written informed consent was obtained from the participants before the experiment.

Instrumentation. Testing was performed in an indoor facility using a motion capture system equipped with 8 infrared cameras (MX-F20; Vicon, Oxford Metrics, Oxford, UK; 250 Hz) that were synchronised with two force platforms (OR6-7; AMTI, Advanced Mechanical Technology, Inc., Watertown, MA, USA; 2000 Hz).

Procedures. Thirty-five reflective markers with a 14-mm diameter were positioned on anatomical landmarks, based on the Vicon Plug-in-Gait full-body model (Oxford Metrics, Oxford, UK). Additionally, four reflective adhesive tapes were attached to the five-iron golf club (1 tape on the toe of the club head, 1 tape on the hosel, and 2 tapes on the shaft). Reflective adhesive tape was used on the golf ball.

The participants completed a self-selected warm-up with stretching and several golf shots for a minimum of 10 min. They performed an initial static, a standing calibration trial. Each participant was then asked to assume their preferred address position, and the ball position was marked invisible to them while the outlines of each foot was visibly drawn on the force platforms for consistent foot positions over multiple swings. The participants were asked to perform a straight shot that they would usually hit on a golf course towards a net 5 m away from them consistently over multiple trials. The participants performed five trials for each of five different ball positions along the M-L direction: 4.27 cm (left from the reference position) (LF), 2.14 cm (LH), 0 cm (reference position), – 2.14 cm (RH), and – 4.27 cm (RF) (Fig. 1). For each trial, the ball position was changed randomly and blindly. The diameter and radius of the golf ball were chosen as 4.27 cm and 2.14 cm (RH), and – 4.27 cm (RF) (Fig. 1). For each trial, the ball position was changed randomly and blindly. The diameter and radius of the golf ball were chosen as 4.27 cm and 2.14 cm, respectively, to displace the ball from the reference position. Thus, each participant performed 25 trials in total, five trials at each ball position. Additional shots were given to participants when they could not complete the full swing (2% of all shots) to complete five shots for each ball position condition. The laboratory coordinate system was set such that the X was anteroposterior (A–P) axis, Y was M–L axis, and Z was vertical axis (Fig. 1) following the right-hand-thumb rule.

Data analysis. The three-dimensional data were smoothed using the Woltring filtering routine with a mean square error of 10 mm. The full swing was divided into 14 swing events using the club shaft angle and body moments. The 14 swing events were address (A), backswing 45° (B45), backswing 90° (B90), backswing 135° (B135), backswing 180° (B180), backswing 225° (B225), transition of pelvis (TP), transition of club (TC), downswing 225° (D225), downswing 180° (D180), downswing 135° (D135), downswing 90° (D90), downswing 45° (D45), and impact (I) (Fig. 2).

The address was defined as the frame immediately before the club initiates its movement away from the ball. In previous studies, the time when the club-head changes its direction along the mediolateral direction was identified as the transition from backswing to downswing (i.e. TC). However, the lower extremities typically start downswing actions before the change in club-head direction. To capture the initiation of downswing by the lower extremities, we added one more event, TP, which was identified as the frame when the pelvis changed its rotational direction. Impact was defined as the frame at which the club makes contact with the ball. The other events (B45, B90, B135, B180, B225, D225, D180, D135, D90, and D45) were identified using the angle of the club shaft.
shaft in the YZ plane. Seventeen dependent variables were calculated at each of the 14 swing events as shown in Table 1. The following directions were considered as positive following the coordinate system shown in Fig. 1: vertical GRF, left foot lateral GRF, right foot medial GRF, anterior GRF, towards the target COP, anterior COP, open shoulder/pelvis angle in the transverse plane (left of the parallel to the target), trunk flexion angle in the sagittal plane, knee/ankle extension angle in the sagittal plane, towards the target COM, and anterior COM.

**Statistical analysis.** To capture the average behaviour throughout the golf swing, we calculated the average over all five trials for each condition under each dependent variable. For statistical analysis, Statistical Parametric Mapping (SPM)\textsuperscript{29–32} based on a random field theory was used to test statistical differences between ball positions using the open source (http://www.spm1d.org) MATLAB (Mathworks Inc., Natick, USA) code. SPM allows for non-directed hypothesis test and helps to control Type 1 error by reducing the number of statistical testing of one-dimensional data (i.e. 14 continuous swing events in our study). More details about the method can be

Figure 1. Participants were standing on 2 square force platforms and executed 5 shots for 5 different ball positions along mediolateral direction. LF, LH, R0, RH, and RF stand for left-full position (4.27 cm left from the preferred ball position), left-half position (2.14 cm left from the preferred ball position), reference ball position (i.e. 0 cm at the preferred ball position or the reference ball position), right-half position (2.14 cm right from the preferred ball position), and right-full position (4.27 cm right from the preferred ball position), respectively. The positive Z direction follows the right-hand-thumb rule.

Figure 2. Fourteen sequential swing events identified in this study including address, 5 events during backswing, 2 events during transition to downswing, 5 events during downswing, and impact: Address (A), backswing 45° (B45), backswing 90° (B90), backswing 135° (B135), backswing 180° (B180), backswing 225° (B225), transition of the pelvis (TP), transition of the club (TC), downswing 225° (D225), downswing 180° (D180), downswing 135° (D135), downswing 90° (D90), downswing 45° (D45), and impact (I).
Table 1. List of kinematic and kinetic variables and descriptions.

| Symbol | Variable name | Description |
|--------|---------------|-------------|
| GRFZ,L & GRFZ,R | Left & right vertical GRF | Ground reaction force along the Z-axis on left & right foot (+: vertical) |
| GRFX,L & GRFX,R | Left & right mediolateral GRF | Ground reaction force along the X-axis on left & right foot (+: lateral) & right foot (+: medial) |
| GRFY,L & GRFY,R | Left & right anteroposterior GRF | Ground reaction force along the Y-axis on left & right foot (+: anterior) |
| COP,L & COP,R | Mediolateral & anteroposterior COP | Centre of pressure on the force plates along the X-axis & Y-axis (+: towards the target & anterior, respectively) |

found elsewhere. We performed SPM on each dependent variable between the address and the impact. The critical significance was set at \( p < 0.01 \) instead of a more traditional \( p < 0.05 \) to partially compensate for the inflation of statistical error associated with multiple variables as suggested in other previous golf studies.

**Results**

SPM analysis showed that the ball position was associated with systematic changes of GRFZ,L, GRFZ,R, GRFX,L, GRFX,R, GRFY,L, GRFY,R, A,L & A,R, A,L & A,R, COMX, and COMY. These differences were between address and early backswing (A, B45, and B90) compared to R0 (40.2 ± 4.2%BW averaged across events then subjects) \( (p < 0.01) \) (Fig. 3a). The opposite trends were found in GRFZ,R by comparing between address and early backswing (A and B45) (Fig. 3b), which showed smaller and greater magnitudes \( (LF: + 2.6\%BW, LH: + 1.3\%BW, RH: – 2.6\%BW, and RF: + 1.6\%BW) \) in the left-sided and right-sided ball positions, respectively, compared to R0 \( (60.7 ± 4.7\%BW) \). These trends disappeared after B90 and B45, and reappeared during the events between downswing and impact (D180, D135, D90, D45, and I) for both GRFZ,L \( (LF: + 2.6\%BW, LH: + 1.3\%BW, RH: – 2.6\%BW, and RF: – 6.6\%BW) \) compared to R0 \( (95.4 ± 10.0\%BW) \), whereas the right-sided ball positions were associated with smaller GRFZ,L magnitudes \( (RH: – 1.1\%BW, and RF: – 1.6\%BW) \) between address and early backswing (A, B45, and B90) compared to R0 \( (40.2 ± 4.2\%BW) \). This showed that the left-sided ball positions were associated with greater magnitudes \( (LF: + 1.8\%BW and LH: + 1.0\%BW) \), whereas the right-sided ball positions were associated with smaller GRFZ,L magnitudes \( (RH: – 1.1\%BW, and RF: – 1.6\%BW) \) between address and early backswing (A, B45, and B90) compared to R0 \( (40.2 ± 4.2\%BW) \). This trend disappeared after B90 and B45, and reappeared during the events between downswing and impact (D180, D135, D90, D45, and I) for both GRFZ,L \( (LF: + 2.6\%BW, LH: + 1.3\%BW, RH: – 2.6\%BW, and RF: – 6.6\%BW) \) compared to R0 \( (95.4 ± 10.0\%BW) \) \( (p < 0.01) \) and GRFZ,R \( (LF: – 2.8\%BW, LH: – 0.7\%BW, RH: + 2.9\%BW, and RF: + 5.7\%BW) \) compared to R0 \( (40.0 ± 10.8\%BW) \), whereas the right-sided ball positions were associated with smaller magnitudes \( (LF: – 2.8\%BW, LH: – 0.7\%BW, RH: + 2.9\%BW, and RF: + 5.7\%BW) \) compared to R0 \( (40.0 ± 10.8\%BW) \) \( (p < 0.01) \) (Fig. 3a,b). In terms of the right foot mediolateral GRF, GRFX,R showed smaller magnitudes (less towards the target) \( (LF: – 0.3\%BW, LH: – 0.3\%BW, RH: – 0.5\%BW, and RF: – 0.6\%BW) \) for both left-sided and right-sided ball positions during early backswing (B45, B90, and B135) as compared to R0 \( (+ 10.2 ± 2.3\%BW) \) \( (p < 0.01) \) (Fig. 3d). This trend disappeared during backswing and reappeared during late downswing and impact (D90, D45, and I), but a different trend reappeared, smaller and greater magnitudes \( (RH: – 1.1\%BW, and RF: – 1.6\%BW) \) between address and early backswing (A, B45, and B90) compared to R0 \( (+ 510.9 ± 27.5\%BW) \). This trend reappeared after B90; however, the same trend \( (LF: + 12.1\%BW, LH: + 3.2\%BW, RH: – 11.4\%BW, and RF: + 1.4\%BW) \) in the left-sided and right-sided ball positions, respectively, compared to R0 \( (+ 3.7 ± 4.0\%BW) \) \( (p < 0.01) \) (Fig. 3d). In terms of the right foot anteroposterior GRF, GRFZ,R showed smaller magnitudes (less anterior direction) \( (LF: – 0.0\%BW, LH: + 1.0\%BW, RH: – 0.7\%BW, and RF: – 0.7\%BW) \) for both left-sided and right-sided ball positions at D135 compared to R0 \( (+ 12.6 ± 3.3\%BW) \) \( (p < 0.01) \) (Fig. 3f). Regarding the mediolateral COP, COPX showed trends towards and distant to the target position values \( (LF: + 9.0\%mm, LH: + 5.1\%mm, RH: – 5.1\%mm, and RF: – 7.9\%mm) \) in the left-sided and right-sided ball positions at D135 compared to R0 \( (+ 10.2 ± 2.3\%BW) \). This trend disappeared after B90; however, the same trend \( (LF: + 12.1\%mm, LH: + 3.2\%mm, RH: – 11.4\%mm, and RF: – 23\%mm) \) compared to R0 \( (+ 662.7 ± 42.2\%mm) \) reappeared at the events between downswing and impact (D180, D135, D90, D45, and I) \( (p < 0.01) \) (Fig. 3g). In terms of the anteroposterior COP, COPY showed trends towards the posterior and anterior direction position values \( (LF: – 1.7\%mm, LH: – 0.5\%mm, RH: + 4.3\%mm, and RF: + 5.2\%mm) \) respectively, in the left-sided and right-sided ball positions at impact \( I \) compared to R0 \( (+ 241.4 ± 43.3\%mm) \). A,L showed that the left-sided ball positions were generally associated with open shoulder angles \( (LF: + 0.5° and LH: – 0.1°) \) at address, the right-sided ball positions were associated with closed shoulder angles \( (RH: – 0.6° and RF: – 1.0°) \) compared to R0 \( (+ 0.2° ± 3.0°) \) \( (p < 0.01) \) (Fig. 3i). This trend disappeared during backswing. However, the same trend, open and closed shoulder angles \( (LF: + 1.3°, LH: + 0.7°, RH: – 0.3°, and RF: – 0.5°) \) respectively, in the left-sided and right-sided ball positions reappeared between downswing and impact \( (TC: D225, D180, D135, D90, D45, and I) \) compared to R0 \( (+ 3.0° ± 1.0°) \). A,R also showed that the left-sided ball positions were generally associated with open pelvis \( (LF: + 1.6° and LH: + 0.8°) \) between downswing and impact \( (TC: D225, D180, D135, D90, D45, and I) \) as compared to R0 \( (+ 19.1 ± 9.3°) \).
downswing and impact (D135, D90, D45, and I) compared to R0 (+ 29.5 ± 9.5°) (p < 0.01) (Fig. 3j). $A_{AKL}$ showed more flexed left ankle angles (LF: + 0.7°, LH: + 0.7°, RH: + 0.6°, and RF: + 0.7°) for both left-sided and right-sided ball positions at D225 compared to R0 (+ 72.5 ± 6.3°) (p < 0.01) (Fig. 3n). $A_{AKR}$ showed generally more extend and flexed right ankle angles (LF: + 1.1°, LH: + 0.7°, RH: + 0.1°, and RF: – 0.4°) between downswing and impact (D225, D180, D135, D90, D45, and I) compared to R0 (+ 82.5 ± 6.3°) (p < 0.01) (Fig. 3o).

In terms of the COM, $COM_{L}$ showed trends towards and distant to the target position values (LF: + 6.7 mm, LH: + 3.0 mm, RH: – 5.7 mm, RF: – 10.1 mm) in the left-sided and right-sided ball positions, respectively.
throughout the whole swing between address and impact compared to R0 (+516.4 ± 36.5 mm) (p < 0.01) (Fig. 3p).

In contrast, COMX showed trends towards the posterior and anterior direction position values (LF: –2.3 mm, LH: –2.0 mm, RH: +1.3 mm, and RF: +1.4 mm) in the left-sided and right-sided ball positions, respectively, between late downswing and impact (D90, D45, and I) compared to R0 (+325.9 ± 29.1 mm) (p < 0.01) (Fig. 3q).

Discussion
We examined the effects of M-L ball position on GRF, body segment and joint angles, and whole-body actions during golf swing, and we found that the M-L ball position systematically influenced the GRFZ,L, GRFZ,R, GRFY,R, GRFX,R, COPY, COPX, AS, AP, AA,L, AA,R, COMY, and COMX (Fig. 3). At address. Our findings on the differences between ball positions at address are consistent with a previous study20. Kim et al. (2018) showed that the left-sided ball position was associated with a greater/smaller vertical GRF on the left/right foot, and a more open position of shoulder segment. In a quasi-static posture at address, the whole-body position demonstrated by COP and COM in the M-L direction can be predicted from the difference in the vertical GRFs of feet (GRFZ,L and GRFZ,R). Consistent with the mechanics, our study reports that the whole-body position demonstrated by COPY and COMY was towards/distant to the target in the M-L direction (Fig. 4a,b). We also found that the shoulder angular position (AS) showed systematic differences between the ball position at address. The shoulder in the left-sided ball position was more open than that at the reference ball position (Fig. 4a), whereas the trend was reversed in the right-sided ball position (Fig. 4b).

During backswing. Our study shows that the trends GRF and COP observed at address continues during early backswing, which suggests that the initial setup (GRFZ,L, GRFZ,R, and COPY) at address caused by the ball position continued during early backswing, demonstrating a chain effect (Fig. 4a,b). The mediolateral GRF on the right foot (GRFz,R) showed a difference between the ball positions during early backswing, where the vertical GRF on the right foot (GRFx,R) generally showed peak magnitude. The mediolateral GRF magnitude at the right foot was smaller (less towards the target) for both left-sided and right-sided ball positions than at the reference ball position during early backswing. The trend COM in the M-L direction (COMz) observed at address continued throughout the whole backswing, which also demonstrated a chain effect (Fig. 4a,b).

During back-to-downswing transition. The difference between the shoulder angles (AS) of the ball positions observed at address reappeared during back-to-downswing transition (TC). However, the shoulder angle during the transition phase showed more closed positions for both the left-sided and right-sided ball positions compared to the reference ball position. The participants rotated their shoulder more and created a closed shoul-
under position during the transition for the left-sided ball positions. This seemed to be a strategy employed by the participants to better utilise the X-factor to absorb greater rotational potential energy during the transition to hit the ball at a longer distance from the club-head at TC when the ball is positioned left. We also found that COM in the M-L direction \( (COM_Y) \) observed at address and backswing continued during back-to-downswing transition (Fig. 4a,b), suggesting a chain effect.

**During downswing.** Many of the kinematic and kinetic variables showed differences during downswing \( \text{GRF}_X, \text{AP}, \text{A}_{L,R}, \text{AA}, \text{COM}_X, \text{and COM}_Y \), whereas the differences between the ball positions observed at address or during early backswing reappeared during downswing \( \text{GRF}_X, \text{AP}, \text{GRF}_Y, \text{COM}_Y, \text{and COM}_X \).

The systematic differences between GRF and COP \( \text{GRF}_X, \text{GRF}_Y, \text{COP}_X, \text{and COP}_Y \) of the ball positions observed at address and during early backswing reappeared during mid-downswing and continued throughout the impact (Fig. 4a,b). The difference in mediolateral GRF on the right foot \( \text{GRF}_{X,R} \) observed during early backswing also reappeared during the later downswing. However, the mediolateral GRF on the right foot during the later downswing showed smaller/greater magnitude (less/more towards the target) in the left-/right-sided ball positions than that at the reference ball position (Fig. 4a,b). The anteroposterior GRF on the right foot \( \text{GRF}_{X,L} \) at the mid-downswing showed smaller magnitude (less anterior direction) for both the left-sided and right-sided ball positions compared to the reference ball position (Fig. 4a,b).

The difference between the shoulder angles \( A_S \) of the ball positions observed at back-to-downswing transition continued throughout the downswing. However, the shoulder angle during the early downswing showed a more open position for both the left-sided and right-sided ball positions compared to the reference ball position, and the same trend was observed for the pelvis angle \( A_P \). The participants rotated their shoulder and pelvis more and created open shoulder and pelvis positions during the early downswing for the right-sided ball position potentially to hit the ball at a shorter distance from the club-head at TC. However, we found that the systematic difference in shoulder angle observed at address reappeared during the mid-downswing, and the same trend was observed in pelvis angle (Fig. 4a,b).

The golf swing during the downswing is executed through linear transition and angular rotation of the body.\(^6,11,12,39–41\) The former can be estimated with the COP in the M-L direction \( \text{COP}_X \), and the latter with the shoulder and pelvis angles \( A_S \) and \( A_P \). COP in the M-L direction during the downswing and impact showed a greater difference in the right-sided ball positions \( \text{RF:} -23 \text{ mm} \) than that in the left-sided ball positions \( \text{LF:} +12.1 \text{ mm} \), whereas the pelvic angle during the downswing and impact showed a smaller difference in the right-sided ball position \( \text{RF:} -0.2^\circ \) than that in the left-sided ball positions \( \text{LF:} +1.6^\circ \), which demonstrates that the proportion of the linear transition of the body is greater in percentage than the angular rotation of the pelvis in the right-sided ball positions.

Furthermore, the left ankle angle \( \text{AA}_L \) was more flexed for both the left-sided and right-sided ball positions compared to the reference ball position during the early downswing (Fig. 4a,b). The right ankle angle \( \text{AA}_R \) was less/more flexed for the left-/right-sided ball positions compared to the reference ball position throughout the whole downswing (Fig. 4a,b).

COM in the M-L direction \( \text{COM}_X \) shows that the whole-body position is more toward/distant to the target in the left-/right-sided ball positions throughout the whole swing (Fig. 4a,b). This observation also confirms that the chain effect of the ball position continuously leads to systematic changes in the final stage of golf swing. COM in the A-P direction \( \text{COM}_Y \) was in a more posterior/anterior position compared to the reference ball position in the left-/right-sided ball positions during late downswing (Fig. 4a,b).

**At impact.** Most of the kinematic and kinetic variables analysed in our study showed differences during downswing continues at impact \( \text{GRF}_X, \text{GRF}_Y, \text{COP}_X, \text{COP}_Y, A_S, A_P, \text{COM}_X, \text{and COM}_Y \), demonstrating the chain effect (Fig. 4a,b). We also found that the anteroposterior COP \( \text{COP}_Y \) was in a more posterior/anterior position compared to the reference ball position in the left-/right-sided ball positions at impact (Fig. 4a,b).

Although our study did not directly investigate club-head kinematics or club-ball interaction at impact since the focus was on the swing action influenced by the ball position, another study by Kim et al. \( \text{(2018)} \) analysed the effect of the M-L direction \( \text{COM}_Y \) on the club-head kinematics and showed that the club path had less/more ‘in–out’ trajectory at impact in the left-/right-sided ball positions.\(^{20} \) In our study, the shoulder angle \( A_S \) is more open during downswing and at impact in the left-sided ball positions. The less ‘in–out’ trajectory of the club-head in the impact in the left-sided ball positions reported in the previous study\(^{20} \) may be due to a more open shoulder angle during the downswing and impact, whereas the increased ‘in–out’ in the right-sided ball positions at impact may be due to a more closed shoulder angle during the downswing and impact (Fig. 4c), demonstrating another chain effect.

**Statistics and practical applications.** Previous studies on golf swing often chose limited discrete swing events for analysis such as address, swing transition, mid-downswing, impact, or the time of the maximum/minimum dependent variable.\(^{28,35,41–43} \) However, our study employed SPM recently introduced in biomechanics to analyse the entire golf swing at different discrete swing events. Since golfers use different swing tempos, and swing events between golfers do not usually occur at the same time in the time trajectory of swing, it was not ideal to apply SPM to the time trajectory. Therefore, we identified and used 14 sequential swing events for SPM analysis to allow the comparison of dependent variables across swing events rather than time trajectories.

Our findings can potentially be informative to golf coaches and golfers. For example, when a golfer shows a lack of shoulder and pelvis rotations during the downswing, the coach can check whether the ball position is too far to the right and move the ball to the left, and then assess whether the golfer demonstrates improved shoulder.
and pelvis rotation for the desired swing flow. Thus, the findings of the current study may provide valuable knowledge to swing coaches and golfers to improve swing and eventually the performance.

**Limitations.** The goal of the study was to investigate if there existed systematic differences in dependent variables at ball positions. Although some variables showed statistical differences at ball positions, the interpretation of the results in practical settings should consider the differences between statistical significance and practical significance. For example, the sizes of some of the effects are very small (e.g., ~1.3 mm differences in COM, between conditions), particularly considering the accuracy of the motion capture system (~2 mm). Although these differences may be statistically significant, they may not carry a practical significance because the differences are larger than the accuracy of the motion capture system.

**Conclusion**
The purpose of this study to investigate how the ball position influences golf swing in relation to the chain effect. Our study found that the M-L ball position systematically influenced the weight distribution, shoulder and pelvis angles, left/right ankle angles, and whole-body action during the golf swing and demonstrated the chain effect. Based on the results of this study, we concluded that the chain effect exists in golf swing: the initial state of the address caused by the ball position can lead to sequential changes in golf swing behaviour.

**Data availability**
Upon reasonable request, the datasets used and analysed during the current study will be made available by the corresponding author.

Received: 20 January 2020; Accepted: 25 November 2020
Published online: 29 January 2021

**References**
1. Hume, P. A., Keogh, J. & Reid, D. The role of biomechanics in maximising distance and accuracy of golf shots. *Sports Med.* **35**, 429–449 (2005).
2. Milburn, P. Summation of segmental velocities in the golf swing. *Med. Sci. Sports Exerc.* **14**, 60–64 (1982).
3. Neal, R., Lumsden, R., Holland, M. & Mason, B. Body segment sequencing and timing in golf. *Int. J. Sports Sci. Coach.* **2**, 25–36 (2007).
4. Cheerham, P. et al. Comparison of kinematic sequence parameters between amateur and professional golfers. in *Science and Golf V: Proceedings of the World Science Congress Golf*, 30–36 (2008).
5. Timmreck, P., Hellström, J., Halvorsen, K. & Thorstensson, A. Elite golfers’ kinematic sequence in full-swing and partial-swing shots. *Sports Biomech.* **9**, 236–244 (2010).
6. Choi, A., Lee, I.-K., Choi, M.-T. & Mun, J. H. Inter-joint coordination between hips and trunk during downswing: Effects on the clubhead speed. *J. Sports Sci.* 1–7 (2016).
7. Joyce, C. An examination of the correlation amongst trunk flexibility, x-factor and clubhead speed. *J. Sports Sci.* 1–7 (2016).
8. Joyce, C. The most important “factor” in producing clubhead speed in golf. *Hum. Mov. Sci.* **55**, 138–144 (2017).
9. Egret, C., Nicolle, B., Dujardin, F., Weber, J. & Chollet, D. Kinematic analysis of the golf swing in men and women experienced golfers. *Int. J. Sports Med.* **27**, 463–467 (2006).
10. McNally, M. P., Yontz, N. & Chaudhari, A. M. Lower extremity work is associated with club head velocity during the golf swing in experienced golfers. *Int. J. Sports Med.* **35**, 785–788 (2014).
11. Ball, K. A. & Best, R. J. Different centre of pressure patterns within the golf stroke I: Cluster analysis. *I. Sports Sci.* **25**, 757–770 (2007).
12. Ball, K. A. & Best, R. J. Different centre of pressure patterns within the golf stroke II: Group-based analysis. *I. Sports Sci.* **25**, 771–779 (2007).
13. Najaﬁ, B., Lee, Eng, J., Wrobel, J. S. & Goebel, B. Estimation of center of mass trajectory using wearable sensors during golf swing. *I. Sports Sci. Med.* **14**, 354 (2015).
14. Wrobel, J. S., Marclay, S. & Najaﬁ, B. Golfing skill level postural control differences: A brief report. *I. Sports Sci. Med.* **11**, 452–458 (2012).
15. Shim, J. K., Latash, M. L. & Zatsiorsky, V. M. Prehension synergies in three dimensions. *J. Neurophysiol.* **93**, 766–776 (2005).
16. Zatsiorsky, V. M., Latash, M. L., Gao, F. & Shim, J. K. The principle of superposition in human prehension. *Robotica* **22**, 231–234 (2004).
17. Shim, J. K., Latash, M. L. & Zatsiorsky, V. M. Prehension synergies: trial-to-trial variability and principle of superposition during static prehension in three dimensions. *J. Neurophysiol.* **93**, 3649–3658 (2005).
18. Morrison, A., McGrath, D. & Wallace, E. Changes in club head trajectory and planarity throughout the golf swing. *Proc. Eng.* **72**, 144–149 (2014).
19. Smith, A., Roberts, J., Wallace, E. & Forrester, S. Professional golf coaches’ perceptions of the key technical parameters in the golf swing. *Proc. Eng.* **34**, 224–229 (2012).
20. Kim, S. E. et al. Biomechanical effects of ball position on address position variables of elite golfers. *I. Sports Sci. Med.* **17**, 589 (2018).
21. Bradshaw, E. J. et al. The effect of biological movement variability on the performance of the golf swing in high-and low-handicap-capped players. *Res. Q. Exerc. Sport* **80**, 185–196 (2009).
22. Zhang, X. & Shan, G. Where do golf driver swings go wrong? Factors influencing driver swing consistency. *Scan. J. Med. Sci. Sports* **24**, 749–757 (2014).
23. Nicklaus, J. *Golf My Way. The Instructional Classic Revised and Updated* 122–123 (Simon & Schuster Paperbacks, 2003).
24. Watson, T. *The Timeless Swing* 87–88 (Atria Books, 2011).
25. Evans, K. & Tuttle, N. Improving performance in golf: Current research and implications from a clinical perspective. *Braz. J. Phys. Ther.* **19**, 381–389 (2015).
26. Woltring, H. J. A FORTRAN package for generalized, cross-validatory spline smoothing and differentiation. *Adv. Eng. Softw.* **1978(9)**, 104–113 (1986).
27. Healy, A. et al. Analysis of the 5 iron golf swing when hitting for maximum distance. *J. Sports Sci.* **29**, 1079–1088 (2011).
28. Chu, Y., Sell, T. C. & Lephart, S. M. The relationship between biomechanical variables and driving performance during the golf swing. *J. Sports Sci.* **28**, 1251–1259 (2010).
29. Mei, Q., Gu, Y., Fu, F. & Fernandez, J. A biomechanical investigation of right-forward lunging step among badminton players. *J. Sports Sci.* 35, 457–462 (2017).
30. De Ridder, R. et al. Multi-segment foot landing kinematics in subjects with chronic ankle instability. *Clin. Biomech.* 30, 585–592 (2015).
31. Herbaut, A. et al. The influence of shoe aging on children running biomechanics. *Gait Posture* 56, 123–128 (2017).
32. Pataky, T. C. One-dimensional statistical parametric mapping in Python. *Comput. Methods Biomech. Biomed. Eng.* 15, 295–301 (2012).
33. Naouma, H. & Pataky, T. C. A comparison of random-field-theory and false-discovery-rate inference results in the analysis of registered one-dimensional biomechanical datasets. *PeerJ*, e8189. https://doi.org/10.7717/peerj.8189 (2019).
34. Pataky, T. C., Vanreterghem, J. & Robinson, M. A. Zero-vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *J. Biomech.* 48, 1277–1285 (2015).
35. Zheng, N., Barrentine, S., Fleissig, G. & Andrews, J. Kinematic analysis of swing in pro and amateur golfers. *Int. J. Sports Med.* 29, 487–493 (2008).
36. Henry, E., Berglund, K., Millar, L. & Locke, F. Immediate effects of a dynamic rotation-specific warm-up on X-factor and X-factor stretch in the amateur golfer. *Int. J. Sports Phys. Ther.* 10, 998 (2015).
37. Han, K. H. et al. Effects of pelvis–shoulders torsional separation style on kinematic sequence in golf driving. *Sports Biomech.* 18, 663–685 (2019).
38. Cole, M. H. & Grimshaw, P. N. The biomechanics of the modern golf swing: Implications for lower back injuries. *Sports Med.* 46, 339–351 (2016).
39. Okuda, I., Gribble, P. & Armstrong, C. Trunk rotation and weight transfer patterns between skilled and low skilled golfers. *J. Sports Sci. Med.* 9, 127 (2010).
40. Horan, S. A. & Kavanagh, J. J. The control of upper body segment speed and velocity during the golf swing. *Sports Biomech.* 11, 165–174 (2012).
41. Joyce, C., Burnett, A., Cochrane, J. & Ball, K. Three-dimensional trunk kinematics in golf. Between-club differences and relationships to clubhead speed. *Sports Biomech.* 12, 108–120 (2013).
42. Zheng, N., Barrentine, S., Fleissig, G. & Andrews, J. Swing kinematics for male and female pro golfers. *Int. J. Sports Med.* 29, 965–970 (2008).
43. Joyce, C., Burnett, A., Cochrane, J. & Reyes, A. A preliminary investigation of trunk and wrist kinematics when using drivers with different shaft properties. *Sports Biomech.* 15, 61–75 (2016).
44. Pataky, T. C. RFT1D: Smooth one-dimensional random field upcrossing probabilities in Python. *J. Stat. Softw.* 71, 1–22 (2016).
45. Jacobson, B. H., Stemm, J. D., Redus, B. S., Goldstein, D. F. & Kolb, T. Center of vertical force and swing tempo in selected groups of elite collegiate golfers. *Sports Biomech.* 8, 1–4 (2005).
46. Sim, T. et al. Analysis of pelvis-shoulder coordination patterns of professional and amateur golfers during golf swing. *J. Motor Behav.* 1–7 (2017).
47. Joyce, C., Chivers, P., Sato, K. & Burnett, A. Multi-segment trunk models used to investigate the crunch factor in golf and their relationship with selected swing and launch parameters. *J. Sports Sci.* 34, 1970–1975 (2016).
48. Merriaux, P., Dupuis, Y., Boutteau, R., Vasseur, P. & Savatier, X. A study of vicon system positioning performance. *Sensors.* 17, 1591 (2017).
49. Cole, M. H. & Grimshaw, P. N. The X-factor and its relationship to golfing performance. *J. Quant. Anal. Sports* 5 (2009).
50. Lephart, S. M., Smoliga, J. M., Myers, J. B., Sell, T. C. & Tsai, Y.-S. An eight-week golf-specific exercise program improves physical characteristics, swing mechanics, and golf performance in recreational golfers. *J. Strength Cond. Res.* 21, 860–869 (2007).
51. Meister, D. W. et al. Rotational biomechanics of the elite golf swing: Benchmarks for amateurs. *J. Appl. Biomech.* 27, 242–251 (2011).
52. Myers, J. et al. The role of upper torso and pelvis rotation in driving performance during the golf swing. *J. Sports Sci.* 26, 181–188 (2008).
53. Lindsay, D. & Horton, J. Comparison of spine motion in elite golfers with and without low back pain. *J. Sports Sci.* 20, 599–605 (2002).
54. Lindsay, D. M., Horton, J. F. & Paley, R. D. Trunk motion of male professional golfers using two different clubs. *J. Appl. Biomech.* 18, 275–281 (2002).

Acknowledgements
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author contributions
Study design: S.E.K., S.C.L., H.D.L. and S.Y.L. Data collection: S.E.K. and J.L. Data processing and analysis: S.E.K. and S.C.L. Statistical analysis: S.E.K. and J.K.S. Writing of manuscript: S.E.K., S.C.L., J.K.S., H.D.L., S.Y.L. and J.L. All authors read and approved the final manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-020-79091-7.

Correspondence and requests for materials should be addressed to J.K.S. or S.-C.L.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
