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Research article

Reducing Knee Joint Load during a Golf Swing: The Effects of Ball Position Modification at Address

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Abstract
As the modern golf swing has changed, the incidence of knee pain in professional golfers is increasing. For those with previous knee injuries, developing a golf-swing modification that reduces knee loading may be necessary to recover performance after injury. The purpose of this study was to test whether ball position modification reduces knee joint load in a golf swing. Thirteen male professional golfers participated in the study. Golf swings were captured using a three-dimensional motion capture system and two force platforms, with conditions for self-selected ball position and eight additional ball positions. Knee internal rotation and adduction moments were calculated. The length of one golf ball (4.27 cm) backward ball position (closer to the golfer) significantly reduced the peak internal rotation moment of the lead knee (- 13.8%) ($p < 0.001$) and the length of one golf ball (4.27 cm) away from the target ball position significantly reduced the peak adduction moment of the lead knee (- 11.5%) ($p < 0.001$) compared with that of the self-selected ball position. Based on these observations, we conclude that the backward ball position modification might be suggested for golfers with anterior cruciate ligament injuries, and the away from the target modification might be suggested for golfers with medial compartment knee osteoarthritis.

Key words: Sports injury, anterior cruciate ligament, osteoarthritis, knee internal rotation moment, knee adduction moment.

Introduction

The need for research on reducing knee loading in golf swings is expanding widely. Recently, professional golfers have seen an increase in ball distance due to increased strength training (Ehlert, 2020) and a change in modern swing techniques (Marshall and McNair, 2013). However, the incidence of knee injuries is increasing. The incidence of knee injuries is still only 4 - 6% of total golfing injuries, but the difficulty in recovering after injuries is a problem (Robinson et al., 2019). In addition, by analyzing the survey from the PGA Champions Tour, which consists of people over the age of 50, approximately 55% answered that they had experienced knee pain during their careers (Baker et al., 2017). Additionally, there is a significant amount of population that have experienced anterior cruciate ligament (ACL) tears during participation in pivoting sports (Melick et al., 2016). Since the amount of golfers is rapidly growing worldwide (Robinson et al., 2021), these findings may reflect in the increasing number of golfers who have experienced an ACL tear. Based on the amount of recreational and professional golfers who may have experienced an ACL tear in other sports, the need for research on golf-swing modification to reduce knee loading may help further enjoyment of the game as well as performance.

Several biomechanical studies have been conducted on loading that exerts stress on the knee during a golf swing. The knee internal rotation and adduction moments on the lead leg at the time of impact are identified as most hazardous (Baker et al., 2017; Gatt et al., 1998; Hooker et al., 2018). The combination of a knee internal rotation moment and tibia anterior shear force is known to be a loading mechanism for an ACL tear (Fleming et al., 2001; Markolf et al., 1995; Meyer and Haut, 2008). Previous studies have, thus, stated that golfers with ACL injuries on the lead knee should pay attention when returning to golf, in particular the knee internal rotation moment (Baker et al., 2017). Nevertheless, to our knowledge, golf-swing modifications that reduce the knee internal rotation moment remain limited. The role of the knee internal rotation moment is to reduce the rotational velocity of the golfer-club system during downswing (Carson et al., 2020; Marshall and McNair, 2013). However, the magnitude of the rotational velocity of the golf-club system is associated with the ball distance (Hellström, 2009), which may be a concern in the development of golf-swing modifications.

Knee adduction moment is the primary loading mechanism of medial compartment knee osteoarthritis (OA) progression (Lynn and Noffal, 2010). Several golf-swing modifications have been developed to reduce the knee adduction moment of the lead knee during a golf swing. Lynn and Noffal (2010) found that a greater toe-out angle of the lead foot at the address (pre-swing) reduces the peak adduction moment of the lead knee compared with the straight foot (Lynn and Noffal, 2010). Additionally, a wider stance width was observed to reduce the peak adduction moment compared with the self-selected stance width (Hooker et al., 2018). The direction that modern medicine is pursuing, referred to as “personalized medicine”, is to tailor precise disease treatment that considers differences in people’s genetic profile and lifestyles (Ashley, 2016). Therefore, the development of more diverse golf-swing modifications for OA golfers will serve as a foundation for the direction pursued by modern medical goals.

Other studies have found that ball position along the anteroposterior (forward/backward) direction alters the knee joint angle in the sagittal plane (Kim et al., 2018). Hence, changes in the knee joint angle due to ball position may also reduce knee loading during the golf swing because the knee flexion angle is a risk factor for ACL injuries during landing tasks (Yang et al., 2018; Yu and Garrett, 2007; Yu et al., 2006). Furthermore, this prior work observed that when the ball was positioned away

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from the target direction reduced the vertical ground reaction force of the lead foot during downswing compared with that of the self-selected ball position (Kim et al., 2021). The reduced vertical ground reaction force may also reduce knee loading in the golf swing.

However, to the best of our knowledge, ball position modification has not been examined in terms of reducing knee joint loads. The purpose of this study was to identify whether ball position modification along the forward/backward (F/B) and toward/away from (T/A) the target directions with respect to the self-selected ball position reduces the knee joint load in a golf swing. We hypothesized that ball position modification would reduce the peak internal rotation and adduction moments of the lead knee during a golf swing.

Methods

Participants

13 males, right-handed Korean professional golfers participated in the study (age, 29.0 ± 4.7 years; height, 1.77 ± 0.07 m; mass, 76.1 ± 8.1 kg). Participants were excluded if they had a history of chronic musculoskeletal system pain or injury, such as inflammation within the last 6 months, or a history of musculoskeletal system surgery or knee injuries that would affect the experimental tests. The study was approved by the Yonsei University Institutional Review Board, and all methods were performed in accordance with the relevant guidelines and regulations. All procedures performed in this study were in accordance with the ethical standards of the Yonsei University (IRB#1040917-201601-SB-104-02) committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Each participant provided informed consent before the experiment.

Procedures

Each participant was provided with the same spandex outfit and shoe type to ensure data accuracy. Then, 35 reflective markers were attached to the participants on a Vicon Plug-in-Gait full-body model (Oxford Metrics, Oxford, UK) using double-sided adhesive tape. Additionally, four reflective adhesive tapes were attached to the 5-iron club (below the grip, mid-point of the shaft, and hosel), and one reflective adhesive tape was placed on the golf ball. The participants underwent 3-D golf analysis using a Vicon motion capture system (8 MX cameras), the accuracy of which was validated in a previous study (~ 2 mm) (Merriaux et al., 2017), at 250 Hz and two force platforms (AMTI, Watertown, MA, USA) at 2000 Hz.

Participants were asked to perform their preferred warm-up, which included several practice golf shots. After the warm-up, participants were asked to take their preferred address position and colored tape was attached next to each foot to guide foot placement in future trials. Finally, the participants were asked to execute five full-swing golf shots hitting the golf ball into a curtain, with the following conditions: self-selected and eight different F/B and T/A ball positions. The F/B ball positions were the backward-full (- 4.27 cm closer to the golfer), backward-half (- 2.14 cm), forward-half (2.14 cm), and forward-full (4.27 cm) with respect to the reference ball position (Figure 1a). The T/A ball positions were the toward-full (4.27 cm toward the target), toward-half (2.14 cm), away-half (- 2.14 cm),

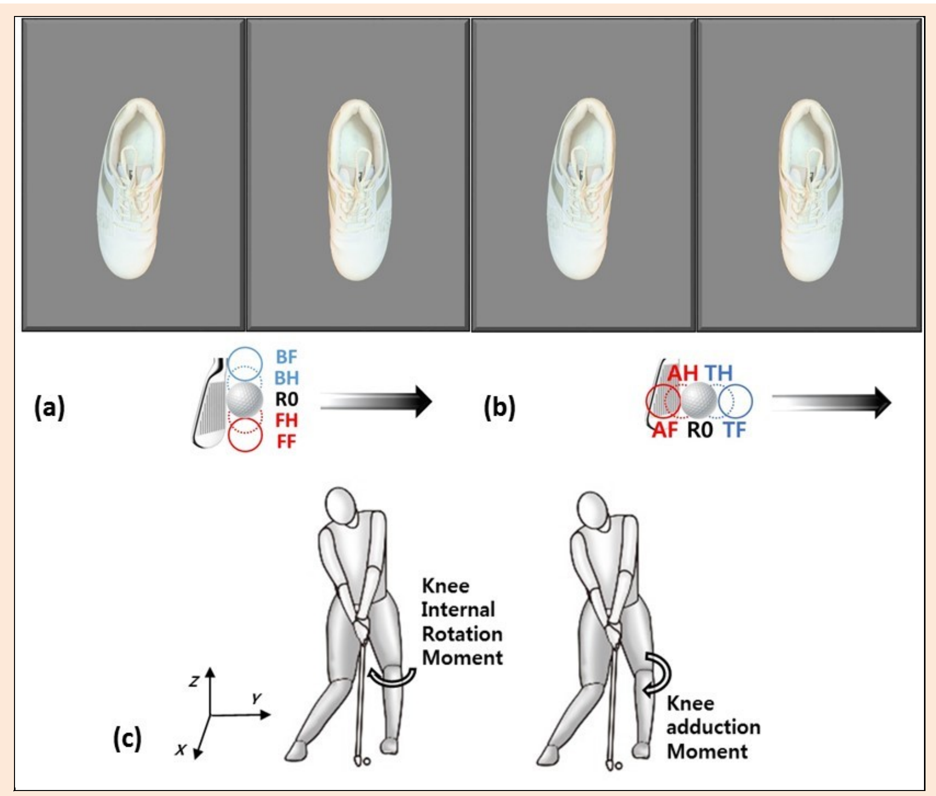

Figure 1. Schematic of experimental settings and the internal rotation and adduction moments of the lead knee at golf impact. (a) BF, BH, FH, and FF stand for the backward-full, backward-half, forward-half, and forward-full, respectively. (b) TF, TH, AH, and AF stand for the toward-full, toward-half, away-half, and away-full, respectively.

and away-full (- 4.27 cm) with respect to the reference ball position (Figure 1b). Those distances were selected for practical application as the 4.27 cm is the length of one golf ball and 2.14 cm is half of a golf ball. The ball position conditions were randomized across participants. A successful trial was noted if all markers were tracked, and additional shots were given to the participants if the trials were unsuccessful. The coordinate system of the *X*-axis was in the anteroposterior direction, *Y*-axis was in the mediolateral direction, and *Z*-axis was in the vertical direction (Figure 1).

Data analysis

Using biomechanical analysis software (Vicon Nexus 2.5, Oxford, UK), the raw marker trajectory data were smoothed using a Woltring filtering routine with a 10 mm^2 mean square error (Woltring, 1986). The knee internal rotation and adduction moments (the tibia segment with respect to the thigh segment in the transverse and frontal planes, respectively) of the lead leg were obtained by processing kinematic and ground reaction force data using an inverse dynamics approach (Ramakrishnan et al., 1987). The moments were normalized to body weight (Baker et al., 2017; Carson et al., 2020; Lynn and Noffal, 2010) and indexed at their first peak (Hooker et al., 2018; Lynn and Noffal, 2010; Purevsuren et al., 2017). There are generally two peaks in the internal rotation and adduction moments during the golf swing, and this study has chosen the first peak for consistent peak timing. In addition, the first peak generally occurs just after impact, while the second peak is near finish (Carson et al., 2020), with pain felt by golfers typically reported near impact (Baker et al., 2017). The average of five trials per position was used to calculate the respective knee joint loads. The direction of the internal rotation moment of the lead knee is negative. The direction of the adduction moment of the lead knee is positive (Figure 1c).

We also calculated club variables such as clubhead speed and path to evaluate any changes in performance. The clubhead speed at impact, the primary determinant of the ball distance, was calculated using the resultant clubhead velocities. The club path at impact, the primary determinant of ball direction, was calculated using the anteroposterior component of clubhead velocities (Sweeney et al., 2013). The impact was defined as the frame at which the clubhead made contact with the ball. The direction of the in-out (the right-side of the parallel of the target line) club path is positive. The average of five trials per position was also used to calculate the respective club variables.

Statistical analysis

We performed a separate one-way repeated measures analysis of variance (IBM SPSS Statistics 24) for the F/B and T/A ball positions for each dependent variable (peak internal rotation and adduction moments of the lead knee and the clubhead speed and club path at impact) for the five ball positions. Furthermore, to determine whether the magnitude of change in the knee joint loads and club variables was related to how much a participant altered their ball position from their self-selected ball position, the overall correlation coefficient was calculated for all participants using the formula in Eq. (1), as suggested (Alexander et al., 1989; Karimpour et al., 2018):

$$\bar{r} = \frac{\sum(n_i - 1)}{\sum n_i - k}\left\{r_i + \left[\frac{r_i(1 - r_i^2)}{2(n_i - 3)}\right]\right\} \quad (1)$$

Where, r_i is the Pearson correlation coefficient for the individual participants, n_i is the number of trials (ball positions in the current study) based on which r_i was calculated, and k is the number of participants. The Bonferroni correlation was used to adjust the Type I error rate of each analysis to $p < 0.0125$ (0.05 alpha level divided by four dependent variables, which include the peak internal rotation and adduction moments, clubhead speed, and club path) (Yu et al., 2006).

Results

Figure 2 shows the internal/external rotation and add/abduction moments of the lead knee during downswing for the F/B and T/A ball positions.

Knee internal rotation moment

The peak knee internal moments showed significant differences between the F/B ball positions ($p < 0.001$). The peak knee internal rotation moment increases in the forward ball positions (1.2% and 5.7%, half and full respectively), and decreases in the backward ball positions (6.5% and 13.8%, half and full respectively), compared to the self-selected reference position (Figure 2a and Table 1). A post-hoc test for pairwise comparisons showed that only with the backward-full among all of the F/B ball positions was significantly decreased with respect to the reference ball position, at which the peak knee internal rotation moment was decreased by 13.8% (BF: - 0.26 ± 0.09 Nm/kg vs. R0: - 0.3 ± 0.08 Nm/kg) ($p = 0.007$) (Table 1).

In addition, the peak knee internal rotation moments also showed significant differences between the T/A ball positions ($p = 0.01$). The peak knee internal rotation moment increases in the toward to the target ball positions (2.4% and 4.1%, half and full respectively), and decreases in the away from the target ball positions (3.3% and 8.9%, half and full respectively), compared to the self-selected reference ball position (Figure 2b and Table 1). However, none of the T/A ball positions were significantly differenced with respect to the reference ball position in the post-hoc test.

Knee adduction moment

The peak knee adduction moment showed no significant difference between the F/B ball positions ($p = 0.03$) (Figure 2c and Table 1).

However, the peak knee adduction moments showed significant differences in the T/A ball positions ($p < 0.001$). The peak knee adduction moment increases in the toward to the target ball positions (5.8% and 5.4%, half and full respectively), and decreases in the away from the target ball positions (3.9% and 11.5%, half and full respectively), compared to the self-selected reference ball position

(Figure 2d and Table 1). The post-hoc test showed that only with the away-full among all of the T/A ball positions were significantly decreased with respect to the reference ball position, at which the peak knee adduction moment was decreased by 11.5% (AF: 0.75 ± 0.15 Nm/kg vs. R0: 0.85 ± 0.15 Nm/kg) (p = 0.01) (Table 1).

Clubhead speed

Clubhead speed showed small but non- significant differences between the F/B ball positions. This difference was not considered as significant due to an extremely conservative adjustment of the Type I error rate (BF: - 1.4%, BH: – 0.8%, FH: 0.6%, and FF: 0.2%) (p = 0.03) (Table 1). In addition, there was no significant difference at the T/A ball positions (p = 0.97) (Table 1).

Club path

The club path showed non- significant differences between the F/B ball positions (p = 0.35) (Table 1). However, it showed significant differences between the T/A ball positions (p < 0.001). The club path decreases (less in-out) in the toward to the target ball positions (18.4% and 10.7%, half and full respectively), and increases (more in-out) in the away from the target ball positions (39.6% and 74.9%, half and full respectively), compared to the self-selected reference ball position (Table 1). The post-hoc test showed that only with the away-full among all of the T/A ball positions were significantly increased with respect to the reference ball position, at which the club path was more in-out by 74.9% (AF: 2.26 ± 1.6 m/s vs. R0: 1.30 ± 1.6 m/s) (p = 0.004) (Table 1).

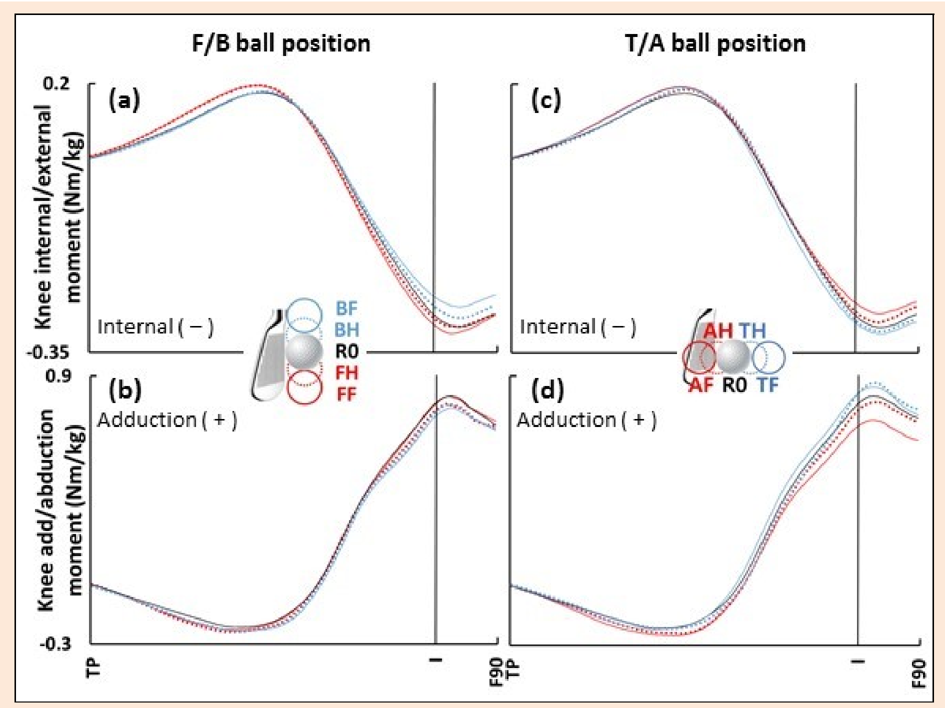

Figure 2. Internal/external rotation and add/abduction moments of the lead knee during downswing for the forward/backward (F/B) and toward/away from the target (T/A) ball positions. BF, BH, R0, FH, and FF stand for the F/B ball positions and TF, TH, R0, AH, and AF stand for the T/A ball positions (see Figure 1). The graphs show the mean trajectories across participants. TP: transition of pelvis, I: impact, F90: club shaft angle of 90° in the frontal plane during the follow-through.

Table 1. Peak internal rotation and adduction moments of the lead knee and club variables for the forward/backward (F/B) and toward/away from the target (T/A) ball positions (see Figure 1) (mean ± SD).

Ball positions	Peak knee internal rotation moment (Nm/kg) Internal (–)	Peak knee adduction moment (Nm/kg) Addduction (+)	Clubhead speed at impact (m/s)	Club path at impact (m/s) In-out (+)	Ball positions
F/B	BF	– 0.26 ± 0.09*	0.8 ± 0.17	34.8 ± 2.4	1.64 ± 1.6
	BH	– 0.28 ± 0.09	0.81 ± 0.17	35.1 ± 2.2	1.71 ± 1.7
	R0	– 0.3 ± 0.08	0.85 ± 0.15	35.3 ± 2.0	1.30 ± 1.6
	FH	– 0.31 ± 0.09	0.82 ± 0.16	35.5 ± 2.4	1.55 ± 1.3
	FF	– 0.32 ± 0.08	0.86 ± 0.17	35.4 ± 2.4	1.42 ± 1.4
	p-value	< 0.001	0.03	0.03	0.35
T/A	TF	– 0.32 ± 0.09	0.89 ± 0.2	35.3 ± 2.4	1.16 ± 1.6
	TH	– 0.31 ± 0.09	0.9 ± 0.18	35.3 ± 2.1	1.06 ± 1.4
	R0	– 0.3 ± 0.08	0.85 ± 0.15	35.3 ± 2.0	1.30 ± 1.6
	AH	– 0.29 ± 0.08	0.81 ± 0.19	35.4 ± 2.0	1.81 ± 1.7
	AF	– 0.28 ± 0.08	0.75 ± 0.15*	35.3 ± 2.4	2.26 ± 1.6*
	p-value	0.01	< 0.001	0.97	< 0.001

* denote p < 0.0125 to R0. BF: backward-full, BH: backward-half, R0: reference, FH: forward-half, and FF: forward-full, TF: toward-full, TH: toward-half, AH: away-half, AF: away-full.

Overall correlation coefficient

In terms of the knee joint loads, the overall correlation coefficient showed that the peak knee internal rotation moment was associated with the F/B ($\bar{r}$ = 0.8, p < 0.001) and T/A ball positions ($\bar{r}$ = 0.67, p = 0.01) (Figure 3a and c), while the peak knee adduction moment was not associated with the F/B ball position ($\bar{r}$ = 0.66, p = 0.02) but only associated with the T/A ball position ($\bar{r}$ = 0.74, p = 0.004) (Figure 3b and d).

In terms of the club variables, the overall correlation coefficient showed that the clubhead speed was not associated with the F/B ($\bar{r}$ = 0.63, p < 0.02) or T/A ball positions ($\bar{r}$ = 0.35, p = 0.25) (Figure 4a and c), whereas the club path was associated with the T/A ball position ($\bar{r}$ = 0.75, p = 0.003), and not associated with the F/B ball position ($\bar{r}$ = 0.51, p = 0.08) (Figure 4b and d).

Discussion

In this study, we identified whether ball position modification along the F/B and T/A directions with respect to the reference ball position (i.e., the self-selected ball position) reduces the knee joint load during the golf swing. The backward-full ball position (closer to the golfer) significantly reduced the peak internal rotation moment of the lead knee, and the away from the target-full ball position significantly reduced the peak adduction moment of the lead knee.

The length of one golf ball (4.27 cm) closer to the golfer (backward-full) ball position reduced the peak internal rotation moment of the lead knee by 13.8% compared with that of the self-selected ball position. The internal rotation moment is considered a crucial loading of the ACL (Fleming et al., 2001; Markolf et al., 1995; Meyer and Haut, 2008). Therefore, for golfers with ACL injuries on the lead knee or recreational golfers who have had ACL injuries from other sports, moving the ball position back one golf ball length is expected to be a useful treatment for life-long enjoyment of the game. This adjustment can be made without a significant impact on clubhead speed.

Moreover, a previous study found that the F/B ball position changes the knee joint angle in the sagittal plane at the address (Kim et al., 2018), and we hypothesized that it may influence the knee joint load as the extended knee angle is a risk factor for ACL injuries in landing tasks (Yang et al., 2018; Yu and Garrett, 2007; Yu et al., 2006). As we hypothesized, the F/B ball positions influenced peak knee internal rotation moment. In terms of the backward ball position, the knee was extended more at the address according to Kim's previous study (Kim et al., 2018) while peak knee internal rotation moment decreased in our study. These results are partially contrary to the studies in landing tasks since the extended knee angle has been shown to be a risk factor for ACL injuries in landing tasks. Therefore, a future study is necessary to investigate whether the such changes in knee joint angle at the address are observed throughout the golf swing.

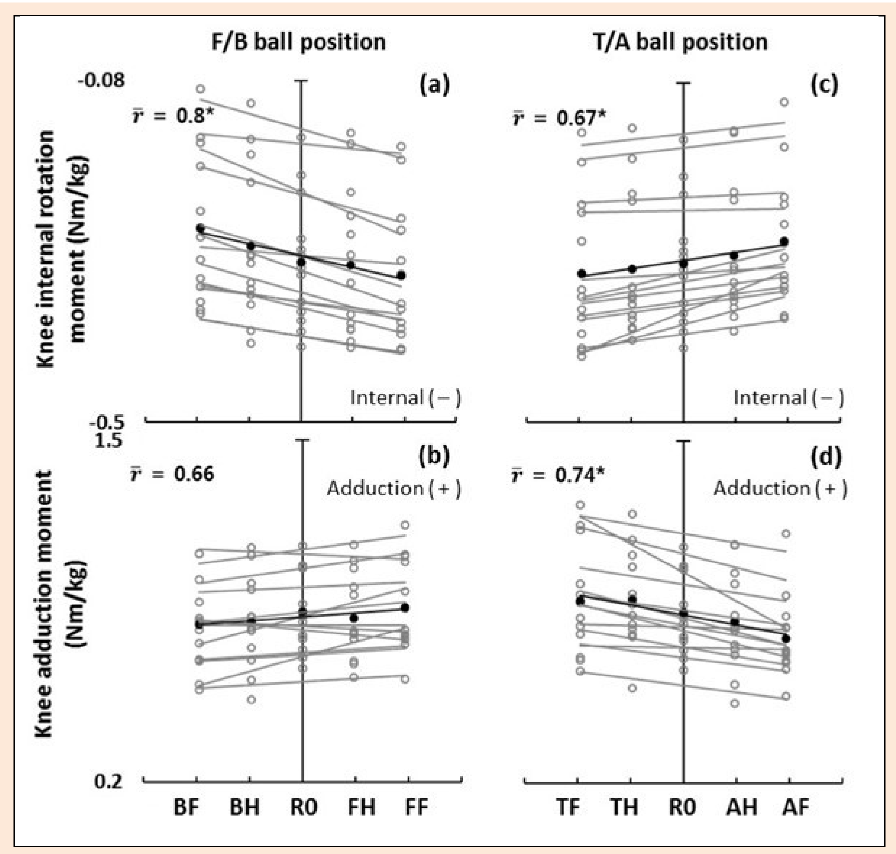

Figure 3. Overall correlation coefficients ($\bar{r}$) between the peak internal rotation and adduction moments of the lead knee and the forward/backward (F/B) and toward/away from the target (T/A) ball positions. Each grey dot represents the mean value of each participant over five shots. Each dark dot represents the average value across the participants. The horizontal axes show the F/B and T/A ball positions (see Figure 1). * significant at p < 0.0125.

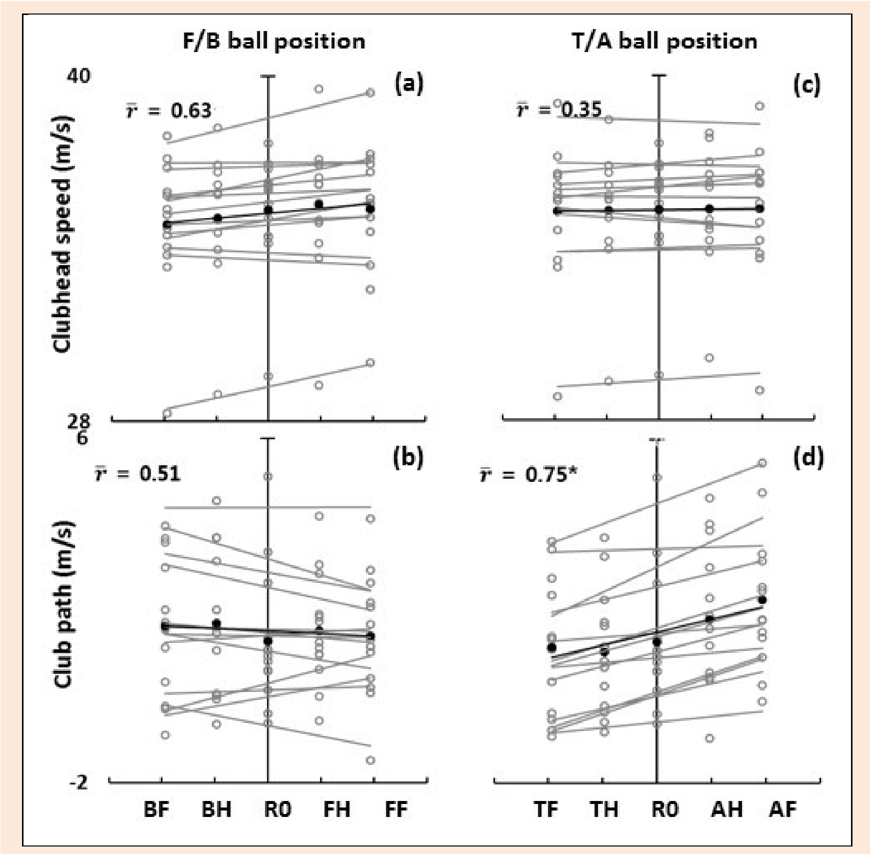

Figure 4. Overall correlation coefficients ($\bar{r}$) between the club variables and the forward/backward (F/B) and toward/away from the target (T/A) ball positions. Each grey dot represents the mean value of each participant over five shots. Each dark dot represents the average value across the participants. The horizontal axes show the F/B and T/A ball positions (see Figure 1). The direction of the in-out club path is positive. * significant at $p < 0.0125$.

The distance length of one golf ball away from the target (away-full) ball position reduced peak adduction moment by 11.5% compared with that of the self-selected ball position, while it also increased an in-out club path (the club path toward the right side of the parallel of the target line) by 74.9%. This may be relevant as the adduction moment is also considered a crucial loading factor of medial compartment knee OA progression (Mündermann et al., 2008). Furthermore, most amateur golfers (the intermediate-skilled group) have swing patterns of the out-in club path (Morrison et al., 2018). Thus, golfers with knee OA and having an out-in club path may prefer the away-full ball position, and serve as a starting point for personalized medicine as mentioned previously.

Lastly, the magnitude of change in the knee joint loads and club variables was related to how much a participant altered their ball position from their self-selected ball position (Figure 4a and d). These correlations indicate that individuals with a greater change in ball position may have a greater reduction in knee loading.

Limitations of study

This study had a few limitations in this study. First, healthy male golf professionals participated in this study; however, patients who had undergone ACL reconstruction or medial compartment knee OA should be investigated in future studies. Second, in terms of ACL loading, the knee internal rotation moment was used in this study, but an estimation of ACL loading using mathematical modeling (Purevsuren et al., 2016) should be used in future studies. Finally, only F/B and T/A ball positions were investigated in this study. The combination of backward and away from the target should be investigated in future studies.

Conclusion

As the need for golf-swing modification to reduce knee loading increases, this study proposes and verifies a change in ball position at the address. We found that the distance length of one golf ball closer to the golfer and away from the target in reference to the self-selected ball position reduced the peak knee internal rotation and adduction moments of the lead leg during the golf swing, respectively. Our findings show that knee internal and adduction moments can be reduced by modifying the ball position at address without compromising clubhead speed. Thus, our findings can be widely used for those who want to use these performance strategies to alter knee loading in golfers.

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Key points

- One ball position (4.27 cm) backward with respect to the self-selected ball position (backward-full) reduces the internal rotation moment of the lead knee during golf swing and is a suggested modification for golfers with ACL injuries.
- One ball position (4.27 cm) away from the target with respect to the self-selected ball position (away-full) reduces the adduction moment of the lead knee during the golf swing and is a suggested modification for golfers with medial compartment knee OA;
- The moving the ball position a distance of one ball length away from target also increases an in-out club path and is a suggested modification for golfers particularly with having an out-in club path.

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