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An Investigation into the Biomechanical Role of Peak Pelvic Rotation in Golf Swing

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Abstract

Background. Clubhead speed (CHS) is a key determinant of golf performance and is influenced by the efficient transfer of energy throughout the kinematic sequence. Peak pelvic rotation angle (PPRA) at the top of the backswing has been proposed as an important biomechanical factor contributing to swing performance; however, previous studies have reported conflicting findings regarding whether greater pelvic rotation is associated with superior outcomes. Consequently, the biomechanical role of PPRA in golf performance remains unclear.

Objectives. This study aimed to (1) determine the association between PPRA and CHS, (2) compare PPRA characteristics between golfers with different performance levels, and (3) clarify the biomechanical role of PPRA in golf swing performance.

Materials and Methods. Eighteen male amateur golfers performed 30 valid swings using a 7-iron under standardized conditions, resulting in 540 analyzed swings. PPRA was measured using an inertial measurement unit (IMU)-based motion capture system, while CHS was assessed using Golfzon Vision. A Linear Mixed Model (LMM) was applied to examine the association between PPRA and CHS, and independent-samples t-tests were used to compare PPRA between the high-CHS and low-CHS groups.

Results. PPRA was significantly associated with CHS ($\beta = 0.164$, $p < 0.001$), indicating that greater pelvic rotation contributed to increased clubhead speed. However, golfers in the high-CHS group demonstrated significantly smaller PPRA values than those in the low-CHS group ($18.49 \pm 1.86°$ vs. $22.45 \pm 4.38°$; $p = 0.019$, Cohen's $d = 1.085$). Additionally, the high-CHS group exhibited lower variability in PPRA, suggesting greater movement consistency.

Conclusions. PPRA contributes to CHS generation; however, superior performance appears to depend more on the optimization and consistency of pelvic rotation than on greater rotational magnitude. These findings suggest that PPRA should be interpreted as a movement coordination characteristic within the kinematic sequence rather than as a performance variable that should simply be maximized.

Keywords: IMU-based, golf biomechanics, peak pelvic rotation angle, clubhead speed.

Introduction

Clubhead speed (CHS) is widely recognized as one of the primary determinants of golf performance because it directly influences ball velocity, shot distance, and competitive success. The generation of CHS depends on the efficient transfer of mechanical energy throughout the body during the golf swing, which is considered a highly coordinated multi-segment movement. Previous biomechanical investigations have established that the golf swing follows a proximal-to-distal kinematic sequence, whereby movement is initiated by the pelvis, followed sequentially by the thorax, lead arm, and finally the club. During the transition from backswing to downswing, each segment changes direction in a coordinated manner, allowing energy to be transferred efficiently through the kinetic chain and ultimately contributing to clubhead acceleration at impact. Consequently, understanding the biomechanical factors that influence this kinematic sequence is essential for improving golf performance and optimizing training strategies (Ball & Best, 2007; Roberts et al., 2024).

Within this kinematic sequence, pelvic motion has been identified as a critical contributor to power generation. As the most proximal rotational segment, the pelvis initiates the transfer of energy from the lower extremities to the upper body and club. Previous studies have shown that skilled golfers generally demonstrate superior pelvic rotational characteristics compared with less-skilled golfers, suggesting an important role of pelvic function in swing performance (Callaway et al., 2012; Cheetham et al., 2008). Furthermore, biomechanical research has consistently reported significant relationships between pelvic kinematics and performance-related outcomes, including CHS, ball speed, driving distance, and impact quality (Myers et al., 2008; Meister et al., 2011; Sim et al., 2017). In addition to pelvic rotation angle, variables such as X-factor, pelvic rotational velocity, pelvis-thorax coordination, and pelvic obliquities have been identified as important contributors to golf swing effectiveness (Meister et al., 2011; Steele et al., 2018).

Among these variables, peak pelvic rotation angle (PPRA) at the top of backswing may represent a particularly important biomechanical factor because it reflects the rotational loading achieved before downswing initiation. From a biomechanical perspective, greater rotational loading may enhance the storage of elastic energy and facilitate its subsequent transfer through the kinetic chain, thereby contributing to higher clubhead speed. Supporting this concept, Myers et al. (2008) demonstrated that trunk and pelvic rotational characteristics are associated with driving performance, whereas Hume et al. (2005) reported that the ability to maximize rotational separation between the shoulders and pelvis is strongly related to driving distance in skilled golfers. These findings suggest that PPRA may play an important preparatory role in generating the rotational energy required for effective downswing acceleration.

Despite the recognized importance of pelvic motion, the specific biomechanical role of PPRA remains unclear. Existing evidence presents conflicting findings regarding whether greater pelvic rotation is beneficial for golf performance. On one hand, several studies suggest that rotational variables contribute positively to CHS and overall swing effectiveness (Myers et al., 2008; Meister et al., 2011). On the other hand, evidence indicates that maximizing pelvic rotation may not necessarily result in superior performance. Myers et al. (2008) reported that golfers seeking to increase clubhead speed often achieve greater upper trunk rotation while simultaneously limiting excessive pelvic rotation at the top of backswing. Similarly, Lynn et al. (2013) found no significant differences in peak pelvic angular velocity between elite and recreational golfers, challenging the assumption that greater pelvic motion automatically leads to better performance.

These contradictory findings may be interpreted through the perspective of motor control theory. According to Bernstein's theory of motor redundancy, the human movement system possesses multiple coordination solutions for achieving the same performance outcome, meaning that skilled performers are not constrained to a single optimal movement pattern (Bernstein, 1967). Similarly, Schmidt and Lee (2019) proposed the concept of motor equivalence, whereby different movement strategies can produce equivalent task outcomes. Applied to golf, these theories suggest that golfers may achieve similar or even superior CHS through different pelvic rotation strategies, provided that energy transfer within the kinematic sequence remains efficient. Therefore, superior performance may depend less on maximizing pelvic rotation magnitude and more on optimizing the coordination and timing of segmental motion throughout the swing. This perspective provides a theoretical explanation for the inconsistent findings reported in previous biomechanical studies and highlights the need to clarify the specific role of PPRA in golf performance.

Consequently, a significant knowledge gap remains regarding whether PPRA should be interpreted as a biomechanical factor that directly enhances performance or as a movement characteristic reflecting individual coordination strategies within the golf swing. Although previous studies have investigated pelvic biomechanics using laboratory-based motion capture systems, relatively little evidence is available concerning the use of wearable technologies to examine the relationship between PPRA and performance outcomes in amateur golfers. Recent advancements in inertial measurement unit (IMU) technology have enabled practical and field-based biomechanical assessment. IMUs have demonstrated acceptable validity for measuring golf swing rotational biomechanics and offer several advantages over traditional motion capture systems, including portability, lower cost, and real-time feedback capabilities (Lee & Lee, 2022; Kim et al., 2023). As a result, IMU-based systems provide a promising opportunity to investigate the biomechanical significance of PPRA in ecologically valid training and performance environments.

Therefore, the present study aimed to investigate the biomechanical role of peak pelvic rotation angle in golf swing performance using an IMU-based motion capture system. Specifically, the purposes of this study were to: (1) determine the association between PPRA and clubhead speed, (2) compare PPRA characteristics between golfers with different performance levels, and (3) clarify the biomechanical role of PPRA in golf swing performance. By integrating biomechanical theory, motor control principles, and wearable sensor technology, this study seeks to contribute to a more comprehensive understanding of how pelvic rotation influences golf swing mechanics and performance.

Material and Methods

Study Design

This study employed a cross-sectional repeated-measures biomechanical design to investigate the role of PPRA in golf swing performance. The design was developed based on the theoretical framework of the proximal-to-distal kinematic sequence, which proposes that rotational energy is transferred sequentially from the pelvis to the thorax, upper extremities, and ultimately the club during the golf swing (Roberts et al., 2024). Within this framework, PPRA at the top of backswing was considered a key biomechanical variable reflecting rotational loading prior to downswing initiation. To address the study objectives, two complementary analytical approaches were adopted. First, a Linear Mixed Model (LMM) was used to examine the association between PPRA and clubhead speed (CHS) while accounting for repeated observations within participants. Second, golfers were classified into high-performance and low-performance groups according to CHS to compare PPRA characteristics between performance levels. This approach was selected to evaluate whether PPRA functions primarily as a performance-related biomechanical factor or as an individual movement strategy within the golf swing.

Participants

A total of 18 male undergraduate students majoring in Golf at Ton Duc Thang University, Vietnam voluntarily participated in this study. All participants met the following inclusion criteria: (1) completion of the course: Golf Swing Technique with Mid-Irons (6, 7, 8) with at least 60 hours of practice, (2) a minimum of 1.5 years of golf experience, (3) right-handed dominance, and (4) no musculoskeletal injuries within the previous six months. Participants had not yet obtained an official handicap (System 36), representing an amateur skill level. The age, height, and body mass of the participants (Mean± SD) were 20.3 ± 1.1 years, 174.72 ± 5.26 cm, and 66.72 ± 9.75 kg, respectively. All participants were informed about the study procedures and provided voluntary consent prior to participation. The study was conducted in accordance with ethical standards for human research.

Procedure and Instruments

In order to ensure consistency across sessions, data gathering was carried out in a controlled 3D golf simulation environment. To reduce variation in equipment settings, participants had a standardised warm-up and familiarity session with a 7-iron club and standardised golf balls before to testing. Pelvic kinematics were recorded using an IMU-based system (Noraxon Ultium Portable Lab), which has been widely used for wearable motion analysis in sports biomechanics. The IMU sensor was securely attached to the sacral region (between the posterior superior iliac spines at the L5-S1 level) following established protocols to capture pelvic rotation during the golf swing (Wolski et al., 2024). The system was calibrated using the MyoMOTION

Fig. 1. Experimental setup including Noraxon Ultium Portable Lab , IMU sensor placement, Golfzon Vision system, 7-Iron Club, NiNox 120fps Camera

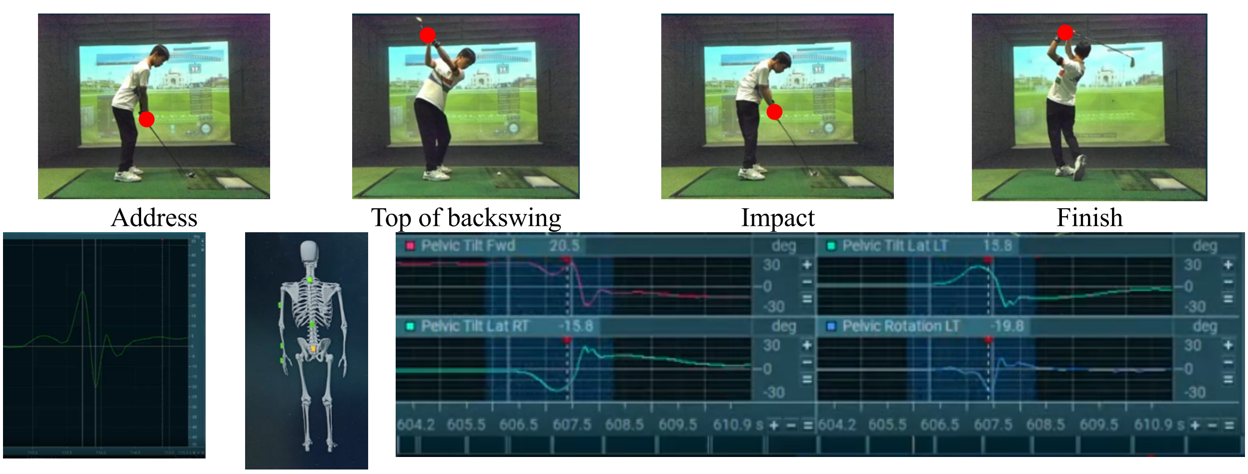

Fig. 2. PPRA measured by IMU across key phases of the golf swing (Address, Top of Backswing, Impact, and Finish)

calibration procedure prior to data collection to ensure measurement accuracy. NiNOX 120 fps camera was used to visually verify swing phases and synchronize kinematic data. CHS was measured using the Golfzon Vision system, which utilizes high-speed optical tracking technology to provide reliable ball and club metrics.

Each participant performed 30 valid golf swings using a 7-iron, resulting in a total of 540 swings included in the analysis. This repeated-measures design was adopted to capture within-subject variability and improve the robustness of the dataset (Tirrell et al., 2018).

Data Collection and Statistical Analysis

Raw data were exported and organized using Microsoft Excel prior to statistical analysis. Descriptive statistics (Mean ± SD) were calculated to summarize participant characteristics and key variables, including PPRA and CHS. Given the repeated-measures structure of the data (multiple swings per participant), a Linear Mixed Model (LMM) was employed to examine the relationship between PPRA and CHS while accounting for inter-individual variability. This approach is appropriate for hierarchical biomechanical data and allows for more accurate estimation of fixed an d random effects (Tirrell et al., 2018).

To further explore performance differences, participants were divided into two groups (high CHS and low CHS) based on the overall mean CHS value. The normality of the data was assessed using the Shapiro-Wilk test. Independent samples t-tests were then conducted to compare peak pelvic rotation angle between groups. Effect sizes were calculated using Cohen's d and interpreted as small (0.2), medium (0.5), and large (≥ 0.8) (Cohen, 1988). The level of statistical significance was set at $\rho < 0.05$. All statistical analyses were performed using IBM SPSS Statistics 26.0

Results

Characteristics of Peak Pelvic Rotation and Clubhead Speed

Descriptive statistics of the main variables are presented in Table 1. The mean CHS of the participants was 34.35 ± 2.59 m/s, representing an intermediate amateur performance level. The mean peak pelvic rotation angle was 20.91 ± 4.06°, with a relatively wide range (13.85° - 27.43°), indicating notable inter-individual variability in pelvic kinematics during the backswing phase. The relatively large standard deviation suggests inconsistent motor control among amateur golfers, particularly in the coordination of pelvic rotation within the kinematic sequence.

Table 1. Descriptive statistics of PPRA and CHS

Variable	N	Min	Max	Mean SD
PPRA(°)	18	13.85	27.43	20.91±4.06
CHS(m/s)	18	31.13	39.40	34.35±2.59

Association between PPRA and CHS

The LMM analysis revealed a statistically significant positive association between PPRA and CHS (Table 2). Specifically, pelvic rotation significantly predicted CHS (β = 0.164, SE = 0.016, t = 9.966, $\rho < 0.001$), indicating that a 1° increase in pelvic rotation was associated with an average increase of 0.164 m/s in CHS, after accounting for inter-individual variability. The 95% confidence interval (0.132 - 0.196) did not include zero, confirming the robustness of this relationship. Variance component analysis indicated substantial between-subject variability (Variance = 3.208) and within-subject residual variance (2.189), resulting in an intraclass correlation coefficient (ICC) of approximately 0.594. This suggests that 59.4% of the variance in CHS can be attributed to differences between individuals.

Table 2. LMM examining for the association between PPRA and CHS

Parameters	Estimate (β)	Std. Error	t	Sig	95% CI
Intercept	30.770	0.751	40.921	0.000	29.229-32.311
PPRA (°)	0.164	0.016	9.966	0.000	0.132-0.196

PPRA Characteristics across performacne levels: High-CHS and Low-CHS Groups

To address the second and third objectives, participants were categorized into high-CHS and low-CHS groups according to the overall mean CHS. Independent-samples t-tests demonstrated significant differences in PPRA between groups (t = -2.643, $\rho = 0.019$). Interestingly, golfers in the high-CHS group exhibited significantly smaller PPRA values (18.49 ± 1.86°) than golfers in the low-CHS group (22.45 ± 4.38°). Furthermore, the standard deviation of PPRA was substantially lower in the high-performance group, indicating greater movement consistency. The effect size was large (Cohen's d = 1.085), suggesting a meaningful practical difference between groups.

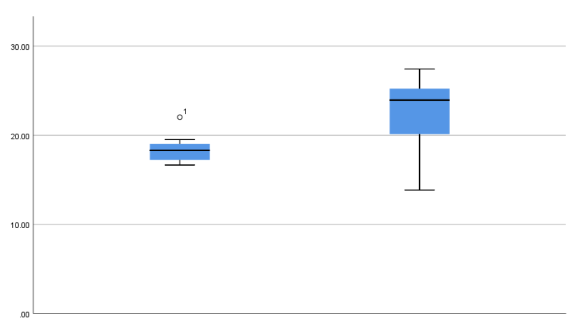

Fig. 3. Distribution of PPRA by High CHS and Low CHS performance group

Summary of findings related to the Biomechanical role of PPRA

The combined findings from the LMM and group comparison analyses indicate that PPRA is associated with CHS but does not appear to function as a performance variable that should be maximized. Although greater PPRA was positively associated with CHS across repeated swings, golfers who achieved higher-CHS demonstrated smaller

Table 3. Comparison of PPRA between high and low CHS groups

Variable	High CHS Group (N = 7), Mean ± SD	Low CHS Group (N=11), Mean ± SD	t(df)	p-value	Cohen's d
PPRA (o)	18.49 ± 1.86	22.45 ± 4.38	-2.643(14.526)	0.019	1.085

Note: *Statistical significance at < 0.05

and more consistent PPRA values than lower-CHS golfers. These findings suggest that the biomechanical role of PPRA may be better understood as a movement coordination characteristic within the kinematic sequence rather than a variable whose magnitude alone determines performance.

Discussion

The purpose of this study was to investigate the biomechanical role of peak pelvic rotation angle (PPRA) in golf swing performance using an IMU-based motion capture system. Three principal findings emerged from the study. First, PPRA demonstrated a significant positive association with clubhead speed (CHS). Second, golfers with higher-CHS exhibited significantly smaller and more consistent PPRA values than lower-CHS golfers. Third, the combined findings suggest that PPRA should not be interpreted solely as a performance-enhancing variable but rather as a movement coordination characteristic that contributes to the optimization of the kinematic sequence.

The positive association observed between PPRA and CHS supports the first study objective and is consistent with previous biomechanical research emphasizing the importance of pelvic motion in golf swing performance. The pelvis serves as the initial segment within the proximal-to-distal kinematic sequence and plays a fundamental role in transferring rotational energy from the lower body to the thorax, upper extremities, and ultimately the club (Neal et al., 2007; Roberts et al., 2024). From a biomechanical perspective, greater pelvic rotation at the top of backswing may increase rotational loading and contribute to the storage of elastic energy that can subsequently be released during the downswing. Previous studies have reported significant relationships between trunk-pelvis rotational characteristics and clubhead speed, suggesting that rotational preparation during the backswing is an important determinant of swing power generation (Hume et al., 2005; Myers et al., 2008; Meister et al., 2011). Therefore, the present findings provide further evidence that PPRA contributes to the generation of CHS by supporting the effective transfer of energy throughout the kinetic chain.

However, the second finding revealed an apparently contrasting pattern. Although PPRA was positively associated with CHS across repeated swings, golfers in the high-CHS group demonstrated significantly smaller PPRA values than those in the low-CHS group. Moreover, PPRA variability was substantially lower among higher-performing golfers. This finding suggests that superior performance is not necessarily achieved through maximizing pelvic rotation magnitude. Instead, it appears that skilled performers may operate within a more optimal range of pelvic rotation while maintaining greater movement consistency. Similar observations have been reported in previous golf biomechanics research, where elite golfers did not always exhibit larger rotational amplitudes than less-skilled golfers despite achieving superior performance outcomes (Lynn et al., 2013). Myers et al. (2008) likewise suggested that increasing upper trunk rotation while limiting excessive pelvic rotation may contribute to higher clubhead speeds, indicating that effective performance may depend on how rotational movements are coordinated rather than on the magnitude of a single kinematic variable.

The apparent discrepancy between the LMM results and the group comparison findings can be interpreted through motor control theory. Bernstein's theory of motor redundancy proposes that the human movement system possesses multiple coordination solutions capable of producing the same performance outcome (Bernstein, 1967). Similarly, Schmidt and Lee (2019) described the concept of motor equivalence, whereby different movement patterns may generate equivalent task results. Applied to golf, these theories suggest that golfers can achieve high clubhead speeds through different movement strategies, provided that the overall kinematic sequence remains efficient. Consequently, larger PPRA values may contribute to CHS generation within an individual golfer, but superior performers may not require greater pelvic rotation if they possess more efficient coordination between the pelvis, thorax, arms, and club. This interpretation provides a theoretical explanation for the contradictory findings reported in previous golf biomechanics studies and supports the notion that movement efficiency is more important than movement magnitude alone.

From a biomechanical standpoint, the present findings suggest that PPRA functions as a component of movement optimization rather than a variable that should be maximized. Previous research has demonstrated that successful golf swings depend on the timing and sequencing of body segments rather than on the isolated magnitude of individual movements (Cheetham et al., 2008; Neal et al., 2007). Excessive pelvic rotation may disrupt the temporal organization of the kinematic sequence, potentially reducing the efficiency of energy transfer from the pelvis to the thorax and club. Conversely, an optimal level of pelvic rotation may facilitate effective rotational loading while preserving segmental coordination. Therefore, the biomechanical role of PPRA appears to involve supporting the organization of the kinematic sequence rather than directly determining performance through larger rotational amplitudes.

An important practical implication of these findings is that golf coaching should not focus exclusively on increasing pelvic rotation range. Traditional coaching approaches often encourage golfers to maximize backswing rotation in an effort to increase power output. However, the present results indicate that higher performance may be characterized by more controlled and consistent pelvic motion rather than greater rotational magnitude. Coaches should therefore prioritize movement quality, timing, and coordination within the kinematic sequence. The use of wearable IMU technology may facilitate this process by providing objective feedback regarding pelvic motion characteristics during training and competition settings. Such information may help coaches identify individualized movement strategies that optimize performance while avoiding excessive or inefficient movement patterns.

Taken together, the findings of the present study suggest that PPRA occupies a dual biomechanical role within the golf swing. On one hand, PPRA contributes to clubhead speed generation through its involvement in rotational loading and energy transfer. On the other hand, superior performance appears to be associated with the optimization and consistency of pelvic rotation rather than its absolute magnitude. Therefore, PPRA should be viewed not simply as a performance variable to be maximized but as a movement coordination characteristic that reflects the efficiency of the golfer's kinematic sequence.

Limitations

This study has several limitations that should be considered when interpreting the findings. First, the sample consisted of a relatively small group of amateur male golfers, which may limit the generalizability of the results to other populations. Second, the study focused exclusively on PPRA and CHS, without considering other biomechanical variables such as X-factor, trunk rotation, ground reaction forces, or muscle activation patterns that may influence golf performance. Third, although IMU technology provides a practical method for field-based biomechanical assessment, measurement errors associated with sensor placement and soft tissue movement cannot be completely excluded. Future research should investigate PPRA within a multi-sensor framework incorporating motion capture, force plate, and EMG measurements to better understand the mechanisms underlying energy transfer during the golf swing. Additionally, studies involving elite golfers, female golfers, and longitudinal intervention designs are needed to determine whether optimizing PPRA and movement consistency can enhance golf performance.

Conclusion

This study demonstrated a significant positive association between Peak Pelvic Rotation Angle (PPRA) and Clubhead Speed (CHS), indicating that pelvic rotational loading contributes to golf swing performance. However, golfers with higher CHS exhibited smaller and more consistent PPRA values than lower-CHS golfers, suggesting that superior performance is not achieved through maximizing pelvic rotation magnitude. Collectively, these findings indicate that the biomechanical role of PPRA extends beyond power generation and is more closely related to the optimization of movement coordination within the kinematic sequence. Therefore, PPRA should be considered a movement-control characteristic that supports efficient energy transfer rather than a performance variable that should simply be increased.

Data Availability Statement

The datasets generated and analyzed during the current study, including IMU-based measurements of peak pelvic rotation angle (PPRA) and clubhead speed (CHS), are available from the corresponding author upon reasonable request.

AI Transparency Statement

During the preparation of this work the authors used ChatGPT 5.1 (OpenAI) in order to support the refinement of English academic writing, including language polishing, structural editing, and alignment with international journal stylistic conventions. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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Дослідження біомеханічної ролі максимального кута повороту таза під час свінгу в гольфі

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Авторський вклад: A – дизайн дослідження; B – збір даних; C – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 8 с., 3 табл., 3 рис., 18 джерел.

Передумова. Швидкість головки ключки (CHS) є одним із ключових чинників результативності в гольфі та залежить від ефективної передачі енергії вздовж кінематичного ланцюга. Максимальний кут повороту таза (PPRA) у верхній точці замаху (backswing) розглядається як важливий біомеханічний фактор, що впливає на ефективність свінгу; однак попередні дослідження повідомляють суперечливі результати щодо того, чи пов›язаний більший поворот таза з вищими показниками результативності. У зв›язку з цим біомеханічна роль PPRA у результативності гри в гольф залишається недостатньо з›ясованою.

Мета дослідження. Метою цього дослідження було: (1) визначити зв›язок між PPRA та CHS; (2) порівняти характеристики PPRA у гольфістів різного рівня результативності; (3) уточнити біомеханічну роль PPRA у забезпеченні ефективності свінгу в гольфі.

Матеріали та методи. У дослідженні взяли участь 18 чоловіків-аматорів, які виконали по 30 валідних свінгів ключкою 7-iron за стандартизованих умов, у результаті чого було проаналізовано 540 свінгів. PPRA визначали за допомогою системи захоплення рухів на основі інерціального вимірювального модуля (IMU), тоді як CHS оцінювали за допомогою системи Golfzon Vision. Для аналізу зв›язку між PPRA та CHS застосовували лінійну змішану модель (Linear Mixed Model, LMM), а для порівняння PPRA між групами з високою та низькою CHS використовували t-тест для незалежних вибірок.

Результати. Встановлено статистично значущий зв›язок між PPRA та CHS ($\beta = 0.164$, $p < 0.001$), що свідчить про те, що більший поворот таза сприяв збільшенню швидкості головки ключки. Водночас гольфісти з високою CHS продемонстрували статистично значуще менші значення PPRA порівняно з гольфістами з низькою CHS ($18.49 \pm 1.86°$ проти $22.45 \pm 4.38°$; $p = 0.019$; d Коена = 1.085). Крім того, група з високою CHS характеризувалася меншою варіабельністю PPRA, що свідчить про вищу узгодженість рухів.

Висновки. PPRA сприяє формуванню CHS, однак вищий рівень результативності, імовірно, більшою мірою залежить від оптимізації та стабільності повороту таза, ніж від максимальної амплітуди його обертання. Отримані результати свідчать про те, що PPRA слід розглядати як характеристику координації рухів у межах кінематичного ланцюга, а не як показник результативності, який необхідно просто максимізувати.

Ключові слова: інерціальний вимірювальний модуль (IMU), біомеханіка гольфу, максимальний кут повороту таза, швидкість головки ключки.

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