Pelvis-Trunk coordination strategies differ across preparatory court movement distance during tennis forehand

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Abstract

Objectives: To examine the effects of on-court movement distances on pelvis-trunk coordination during forehand strokes. **Methods:** Eighteen male college tennis athletes participated in this study. A one-way repeated-measures ANOVA with Statistical Parametric Mapping was used to determine differences in pelvis-trunk coordination in the transverse plane across the three movement distances~~conducted~~, and Pearson's correlation analysis was used to determine the relationships between each of the four pelvis-trunk coordination features on the dominant and non-dominant side and racket speed. **Results:** Significant differences were observed for different movement distances in the non-dominant pelvis-trunk continuous relative phase (CRP) during 23-41% of the acceleration phase (p=0.016, $F_{2,34}$=5.901) and in the dominant pelvis-trunk CRP during 76-100% of the acceleration phase (p=0.016, $F_{2,34}$=5.946). For the minimum distance, significant correlations with racket speed were found in the mean CRP (r=-0.889, p=0.001) and peak CRP (r=-0.488, p=0.04) for the non-dominant side, and the mean CRP (r=-0.478, p=0.045) for the dominant side. Regarding medium distances, significant correlations with racket speed were observed for the non-dominant side in the mean CRP (r=-0.493, p=0.037), peak CRP (r=-0.628, p=0.005), and maximum positive CRP slope (r=0.477, p=0.046). For the dominant side, significant correlations with racket speed were noted for peak CRP (r=0.551, p=0.018) and maximum positive CRP slope (r=0.514, p=0.029). At the maximum distance, significant correlations with racket speed were identified for the dominant side in the maximum positive CRP slope (r=0.580, p=0.012) and maximum negative CRP slope (r=0.566, p=0.014); however, there was no significant difference in racket speed at impact when approaching from different distances. **Conclusion:** These findings underscore the ~~critical~~ role of pelvis-trunk

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Commented [A3]: Indicate distances in brackets coordination in enhancing racket speed, particularly under varying task constraints. Coaches and players should focus on developing adaptable coordination strategies for optimizing performance across different movement distances.

Keywords: CRP, SPM, Coupling, Variations, Tennis, Distance-dependent

Introduction

In modern tennis, the forehand is the most commonly executed stroke[1,2], with more than 80% of shots during a match occurring while the player is moving[3,4]. A key challenge when performing the forehand is the court distance players must cover rapidly to intercept and successfully return their opponent's shot[3,4]. Both tennis coaches and players agree that without efficient court movement, even the most skilled strokes lose their effectiveness[5]. However, despite its significance, limited research has examined the mechanics of court movement or explored perception-action coupling in tennis forehands. Giles and Reid [5] investigated how move speed impacts stroke kinematics in professional male and female players, they found that female players reduced their preparatory trunk rotation by 14% when moving at high move speeds, whereas male players maintained similar racket head speed. Unfortunately, this study focused solely on kinematic variations in isolated joints or segments during specific events, without exploring the relationship between these variations and racket speed.

Pre-impact racket speed is a primary predictor of the ball speed generated by a tennis stroke[6,7]. Previous research has predominantly examined the relationship between biomechanical parameters of individual joints or segments, such as the shoulder[8], the trunk[9,10], and pelvis[11] and racket speed. However, body segments are mechanically linked, meaning the movement of one segment induces predictable movements in connected joints, creating a coupling effect within the kinematic chain[12] , the sequence or timing of movements also means that contributions to movement outcomes are a factor in biomechanical contributions. Furthermore, analyzing only isolated segments or event-specific kinematics may offer an incomplete understanding of the motor control strategies required for executing complex movements that involve the coordination of multiple segments[13].

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In many sports, high-speed upper extremity movements require coordination that transfers forces from the lower extremities through the pelvis and trunk to the upper body. Axial rotation of the pelvis and trunk in the transverse plane is considered a critical link in whole-body coordination, a concept supported by practitioners who emphasize training the trunk and core musculature. Less skilled athletes often exhibit "blocked" (unison pelvis and trunk rotation) during high-effort movements, such as overarm throwing or striking. However, as skill improves, this may transition to “differentiated” rotation[14]. These early qualitative observations have produced mixed findings in biomechanics, motor development, and motor control research, as axial rotations of the pelvis and trunk depend on various factors such as skill level, stance, and task constraints. Sequential axial rotation of the pelvis and trunk over a short period is typically small and has not consistently been observed in highly skilled professional athletes, such as in baseball pitching[15] or the full golf swing[16,17]. Similar variations in pelvis-leg transverse plane coordination have been reported in professional soccer players during kicking[18]. In summary, while sequential coordination between the upper and lower extremities is generally strong in maximum-effort movements, the role sequential/differentiated pelvis and trunk axial rotation (a.k.a. the X-factor in golf [13]) remains unclear across many sports. Multiple studies on the golf swing and regression analyses of large groups of golfers have demonstrated

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Given the gaps identified in the literature, this study aimed to examine how different movement distances affect pelvis-trunk coordination. Another secondary aim was to investigatethe relationship between coordination features and racket speed during the forehand stroke. As movement distance increases, the system is expected to require more resources to respond to perturbations, so we hypothesize that this would result in significant differences in the pelvis-trunk coordination pattern, with greater variability, and that a larger number of coordination features would show significant correlations with racket speed.

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Materials and Methods

Participants

Eighteen male college athletes (age: 23.6 ± 2.2 years, body mass: 75.1 ± 6.5 kg, height: 175.2 ± 6.8 cm, and experience: 10.9 ± 3.1 years) from a local college tennis team participated in this study. The athletes had an International Tennis Number (ITN) ≥ 4, meeting the ITN standards, and trained for 20 hours per week. To meet the inclusion criteria, each participant was required to have completed a minimum of six years of structured tennis training and competition. Additionally, all participants were required to be in good health, with no current or chronic injuries in the past six months. To ensure adequate statistical power of 80%, the required sample size was calculated using G*Power software (version 3.1.9.7). The repeated-measures analysis indicated that at least 18 participants were needed, with parameters set at $\alpha = 0.05$, $\beta = 0.8$, and $r = 0.70$. This study adhered to the principles outlined in the Declaration of Helsinki. The study protocol was explained to all participants, and written informed

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consent was obtained. The protocol was approved by the Jeonbuk National University Institutional Review Board and conducted in accordance with relevant guidelines and regulations (JBNU2022-04-008-002).

Protocol

To minimize the effects of learning and fatigue on the formal experiments, all participants visited the laboratory twice. During their first visit, demographic variables were recorded, and a maximum movement distance test was conducted. Participants first completed a specific warm-up program, which included five minutes of low-intensity sideways and acceleration runs, followed by at least ten minutes of groundstrokes at submaximal speed. After the warm-up, the maximum movement distance test was performed. In this test, participants self-selected a distance and executed forehand strokes using crossover step footwork, directing the ball toward the center of a circle with a 1-meter diameter positioned above the ball machine. All participants followed a standardized down-the-line stroke protocol[5], and adopted an open stance for varying movement distances. Consistent with previous studies, a ball machine (The Tennis Ball Machine PRO, Seoul, South Korea) delivered new balls (Wilson TRAINER) with a standard rotation and speed (25.3 ± 0.4 m/s) to the same stroke position through machine speed model setting for each participant[1,10]. To replicate the environment of a real competition, the circle was placed approximately 6 meters from the participant and 1.3 meters above the ground, reflecting the attacking shots scenarios and the net height. The distance was gradually increased in half-length increments from the ground to the left or right greater trochanter of the femur for each participant until they could no longer effectively execute the forehand stroke technique or maintain accuracy. The maximum movement distance was recorded, and the mean of five trials was used to determine three distances: (a) 100%, (b) 75%, and (c) 50% of the maximum movement distance, reflecting the different preparatory court movement task constraints (Figure 1a). In this study, the average maximum movement distance was 3.47 ± 0.21 meters.

Formal experiments were conducted after a minimum of 48 hours. Participants were instructed to avoid caffeinated beverages for at least eight hours prior to the trial. All participants were tested at the same time of day and were required to wear their own tennis shoes and use their own rackets during the test to minimize the influence of external factors on stroke performance. A single researcher applied 57 reflective markers[22] (14 mm; Biomech Marker Set, OptiTrack, Corvallis, OR, USA) to specific anatomical landmarks on the participants' bodies (Figure 1b). A 15-segment model was created, including the feet, shanks, thighs, pelvis, trunk, head, bilateral upper arms, forearms, and hands.

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Additionally, four markers were placed on the tennis racket, positioned at the 3 o'clock and 9 o'clock positions on the racket head and shaft to capture its trajectory[10]. The same warm-up program from the first laboratory visit was performed to ensure all participants had a similar stroke feeling as in a match scenario and adapted to the markers attached to their bodies. To minimize learning effects, the ball was placed in the machine at random intervals unknown to the participants. They were instructed to stroke the ball with maximum effort, aiming for accuracy by hitting the circle with down-the-line strokes. The first five successful strokes at each distance were included for further analysis. Participants rested for more than two minutes between trials, or until they reported no fatigue, to ensure they maintained their initial performance levels. After each stroke, participants promptly returned to the starting position. The impact height was adjusted according to the position of each participant's hip joint by adjusting the launch angle of the machine[1,10].

[Figure 1]

Fig. 1. Set up description: (a) marker spot position; (b) experiment environment simulation. The black dotted line represents the maximum movement distance; the green dotted line represents the medium movement distance; the red dotted line represents the minimum movement distance; and the arrow represents the move direction.

2.3 Data collection

A motion capture system (OptiTrack, Natural Point, Inc., Corvallis, OR, USA) equipped with 13 high-resolution cameras was used to record the 3D trajectory of the reflective markers during the forehand stroke motion at a frame rate of 240 Hz, from the start position until the return to the start position. Static models were generated for each participant following a standing calibration trial to determine individual body segment parameters. Reflective tape was applied to the tennis ball to accurately capture the moment of impact.

2.4 Data processing

The raw data were imported into Visual 3D software (Professional 6.0; C-Motion Inc., Germantown, MD, USA) and low-pass filtered using a fourth-order, zero-lag Butterworth filter with a cutoff frequency of 6 Hz[22,23]. The pelvis and trunk rotation angles in the transverse plane were calculated by the distal segment relative to the proximal segment using an X-Y-Z cardan rotation sequence[18]. Specifically, the dominant pelvis angle was calculated as right thigh to pelvis, the non-dominant pelvis angle was calculated as left thigh to pelvis, and trunk angle was calculated as pelvis relative to trunk[18]. Angular velocities were calculated from the first-order derivatives of the angles using Visual 3D software. For right-handed players, the right and left sides were defined as the dominant and non-dominant pelvis and trunk, respectively. To standardize the data, global mediolateral

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data for the two left-handed players were reversed, allowing all players to be analyzed as right-handed[24].

The phase of interest was the period from the beginning of the forward rotation of the racket to the moment of impact, defined as the acceleration phase. This phase was identified by analyzing the trajectories of the markers on the racket head and the reflective markers on the ball[24]; both stroke events were visually inspected and confirmed using Visual 3D and video recordings. Additionally, the resultant speed of the racket was computed in Visual 3D as the 3D resultant velocity of the racket in three planes of motion at the one frame before impact[1,10].

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A custom MATLAB code (version R2022b; MathWorks, Natick, MA, USA) was used to compute the non-dominant and dominant pelvis-trunk CRP curves. Consistent with a previous study of golf swing[13], CRP curves were established using four steps. First, joint data were normalized to 101 data points corresponding to the acceleration phase. Second, a phase plane for each joint was created by plotting the angle (θ) and angular velocity (ω), with values normalized to their relative minimum and maximum, resulting in a range from -1 to 1. Third, the phase angle (∅) was calculated calculated at each data point as $\emptyset = \tan^{-1}(\omega/\theta)$. Finally, the CRP angle was calculated as $\emptyset$ pelvis - $\emptyset$ trunk.

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A CRP value of 0° indicated that the two joints were moving in the same direction (“in-phase”), while values of -180° or 180° indicated that the joints were moving in opposite directions (“out-of-phase”). Positive CRP values signified that the trunk position was ahead of the pelvis, and a positive slope denoted that the trunk was rotating faster than the pelvis, whereas a negative slope indicated the opposite[13,20]. Variability was calculated as the standard deviation of the CRP data points across the acceleration phase for all trials and participants.

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Coordination pattern features

To evaluate the relationship between pelvis-trunk coordination and racket speed at impact, the following features of the CRP were extracted: a) the mean value of the CRP, to quantify the average difference in rotation movement between the pelvis and trunk segments; b) the peak value of the CRP, to identify the timing of changes in the dynamic pelvis-trunk coordination pattern; c) the maximum positive CRP slope, to measure the rate at which the trunk rotates faster than the pelvis; and d) the maximum negative CRP slope (slope = [Y2-Y1]/[X2-X1]), to measure the rate at which the pelvis rotates faster than the trunk. Four features were extracted from the CRP curves for both the non-dominant and dominant sides. Microsoft Excel (version 2019; Microsoft Corp., Redmond, WA, USA) was used for all feature extractions and calculations. To determine the relationship between intersegment coordination features and racket speed, players were categorized into two subgroups based on more homogeneous racket speeds at impact observed at each movement distance.

2.6 Statistical analysis

To test the hypothesis that movement distances have no effect on the pelvis-trunk CRP, the entire time series was statistically examined using Statistical Parametric Mapping (SPM) one-way repeated-measures ANOVA. Frist, the test statistics (SPM{F} and SPM{t}) were calculated. The F and t-statistics are qualitatively the same as the effect sizes, and can be used as indicators of practical significance. Random field theory was applied to control the Family-wise type I error rate via a smoothness-dependent correction for multiple comparisons, with the family-wise type I error rate set at 0.05. The critical threshold (F* or t*) is calculated, ,and if the test statistic trajectory exceeded the critical thresholds, the null hypothesis was rejected, and the difference was considered statistically significant. Finally, the p-value was calculated for each suprathreshold cluster. If a significant main effect was identified, paired comparisons were conducted using SPM{t} tests with Bonferroni corrections to determine the location of the differences. The alpha level for pairwise contrasts was adjusted for the number of comparisons per dependent variable ($N = 3$, $\alpha = 0.017$). SPM analyses were executed using the open-source code (www.spm1d.org) within the MATLAB software.

The normality of discrete CRP feature data was analyzed using the Shapiro-Wilk test, and all data were confirmed to be suitable for parametric analysis. A one-way ANOVA was used to assess whether racket speeds differed when the ball was impacted at the three movement distances. Pearson's correlation analysis was conducted to examine the relationships between CRP features and racket speed. All statistical analyses were conducted using SPSS (SPSS Inc., Chicago, IL, USA), and the statistical significance level was set at $p < 0.05$.

Results

At impact, racket speed was 29.9 ± 4.7 m/s for the minimum movement distance, 30.4 ± 4.8 m/s for the medium movement distance, and 29.2 ± 2.1 m/s for the maximum movement distance, with no significant differences observed.

The mean and standard deviation of the non-dominant and dominant pelvis-trunk CRP curves during the acceleration phase are presented in Figure 2. The results of the SPM one-way repeated-measures ANOVA indicated a significant main effect of movement distance on the non-dominant (Figure.2a, 23–41%, p=0.016, $F_{2,34}$=5.901) and dominant (Figure.2b, 76–100%, p=0.005,

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$F_{2,34}$=5.946) pelvis-trunk CRP during the acceleration phase. However, post-hoc analysis using the SPM{t} test revealed no significant differences in CRP curves between the non-dominant and dominant pelvis-trunk across conditions.

Table 1 presents the correlation coefficients between pelvis-trunk coordination features and racket speed at impact for different movement distances. Notably, three, five, and two CRP features were significantly correlated with racket speed for the minimum, medium, and maximum movement distances, respectively. At the minimum movement distance, significant correlations with racket speed were observed for the mean CRP (r = -0.889, p = 0.001) and peak CRP (r = -0.488, p = 0.04) for the non-dominant side, as well as for the mean CRP (r = -0.478, p = 0.045) for the dominant side. For the medium movement distance, significant correlations with racket speed were found for the mean CRP (r = -0.493, p = 0.037), peak CRP (r = -0.628, p = 0.005), and maximum positive CRP slope (r = 0.477, p = 0.046) for the non-dominant side. Significant correlations were also observed for the peak CRP (r = 0.551, p = 0.018) and maximum positive CRP slope (r = 0.514, p = 0.029) for the dominant side. At the maximum movement distance, significant correlations with racket speed were identified for the maximum positive CRP slope (r = 0.580, p = 0.012) and maximum negative CRP slope (r = 0.566, p = 0.014) for the dominant side.

Figure 3 presents the mean and standard deviation of the CRP curves for two subgroups: (1) the nine participants with the fastest racket speeds and (2) the nine participants with the slowest racket speeds.

[Table 1]

[Figure 2]

Fig. 2. Non-dominant and dominant pelvis-trunk continuous relative phase (CRP) curves and standard deviations in different movement distances during the acceleration phase; the black bar represents the time and SPM statistics results during which the differences occurred

[Figure 3]

Fig. 3. Mean and standard deviation of the continuous relative phase (CRP) curves of the nine participants with the fastest racket speed (solid line) and the other nine participants with the slowest racket speed (dashed line) at different movement distances

Discussion

The findings of the present study supported several hypotheses, demonstrating that pelvis-trunk The

findings of the present study supported several hypotheses, demonstrating that pelvis-trunk coordination varied in transverse plane on both the dominant and non-dominant sides with changes in movement distance. Furthermore, as movement distance increased, there was a disproportionate change in the number of coordination features significantly correlated with racket speed.

Pelvis-trunk CRP at different movement distances

Consistent with our hypothesis, a significant main effect of movement distance on pelvis-trunk CRP was observed. As movement distance increased, CRP values for non-dominant pelvis-trunk coordination progressively decreased during the pre-acceleration phase, indicating a reduction in the pelvis's posterior rotation position relative to the trunk. Conversely, CRP slopes for dominant pelvis-trunk coordination progressively increased during the post-acceleration phase, suggesting that the pelvis's anterior rotation was faster than the trunk's. These variations in pelvis-trunk coordination patterns align with findings from a study by Giles and Reid [5], which examined the effect of different entry speeds (analogous to movement distance in our study) on professional female players. Their study reported a decrease in trunk rotation prior to ball impact. However, trunk rotation in professional male players was unaffected by entry speed, likely due to differences in skill levels. The college athletes in our study demonstrated hitting strategies resembling those of professional male The college athletes in our study demonstrated hitting strategies resembling those of professional male players when performing a simpler task. However, in more extreme tasks, the pattern of pelvis-trunk coordination contradicted the typical proximal-to-distal sequence observed in the kinematic chain. The strategy for addressing the "degrees of freedom problem" appeared to depend on the interaction between movement distance and expertise level[5,25,26].

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Regarding the temporal region where the significant main effect of movement distance occurred, the SPM statistics indicate that the non-dominant pelvis-trunk CRP adopted an in-phase coupling strategy during the pre-acceleration phase (23-41%). This suggests a decrease in the pelvis-trunk separation angle, which can be explained by the stretch-shortening cycle principle[13]. To counteract the increased lateral momentum and ground reaction force generated by greater movement distances, players delay the X-factor stretch[20]. In contrast, the dominant pelvis-trunk CRP was observed during the post-acceleration phase (76- In contrast, the dominant pelvis-trunk CRP was observed during the post-acceleration phase (76-100%). The CRP curves reveal that the slope increases disproportionately compared to the absolute CRP value as movement distance increases, suggesting that muscular strength may play a more critical role than range of motion. This interpretation aligns with findings by Seeley, et al. [27] who reported that maintaining higher post-impact ball speeds was more dependent on peak joint angular velocity than on peak joint angle, which disproportionately increased. The trunk as the distal link in the kinetic chain during tennis strokes, exhibits minimal relative change compared to the pelvis. This likely ensures stroke accuracy and maintains consistency in distal movement. These findings align with the "leading joint hypothesis", which emphasizes the importance of proximal joint coordination in facilitating effective distal movements[24,28]. Indeed, since the mean number of strokes required to obtain five successful trials was 5.8 ± 0.6 and 5.9 ± 0.7 at the minimum and maximum movement distances, respectively, accuracy was not negatively impacted by increases in movement distance. This may explain why differences in dominant pelvis-trunk CRP at different movement distances were observed prior to the stroke. The time-series data provided by the SPM approach highlight the role of non-dominant and dominant pelvis-trunk coupling in adapting to task variations across different temporal regions. We suggest that players, particularly those engaged in unilateral motor skills such as tennis, should focus on strengthening core muscles, including the external oblique abdominal muscles, to enhance the non-dominant side's ability to initiate body rotation and maintain dynamic balance.

Further analysis revealed that coordination variability (standard deviation) in the dominant pelvis-trunk was lower than in the non-dominant pelvis-trunk across different movement distances, consistent with the findings of Brito, et al. [29] regarding a 1.5 meters moving distance forehand stroke task. In contrast, a study on golfer's downswings by Choi, et al. [13] found smaller coordination variability in the dominant pelvis-trunk compared to the non-dominant side. A possible explanation for this difference is the absence of task constraints in the golf downswing. As movement distance increased, coordination variability in both the non-dominant and dominant pelvis-trunk also increased, likely due to the

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Commented [A33]: Put better in parentheses. Use the citation in parentheses whenever possible increased task demands on the system, which require more resources to achieve the task goal and consequently greater variability for increased flexibility[30,31]. However, Giles and Reid [5] reported that professional male players maintained stable trunk postures on both the non-dominant and dominant sides as move speed increased, which could be attributed to skill level inconsistencies influencing the results[25]. Findings from golf support Newell's ecological dynamics theory, which posits that task constraints (e.g., movement distance) and self-organization (e.g., skill level) should both be considered when analyzing complex temporal and spatial actions[32]. Notably, smaller variability might result in a more concentrated distribution of stress across tissues, potentially increasing cumulative loads on internal body structures. This could contribute to mechanisms of repeated loading and high torsional stress, leading to overuse injuries in the trunk and lower back of professional athletes[30,33,34]. This finding may inform injury prevention strategies, future prospective training research still need to confirm this hypothesis. Players employing varied techniques to develop racket speed while minimizing injury risk, such as different stances and stroke directions may be used as potential application in the future.

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Relationship between CRP features and racket speed

When comparing the CRP curves with racket speed, a trend emerged indicating that players with the fastest racket speeds adopted different pelvis-trunk coordination strategies on the non- dominant side compared to those with the slowest racket speeds, particularly at the minimum movement distance. For players with the slowest racket speeds, the trunk played a dominant role throughout the movement. Conversely, for players with the fastest racket speeds, the pelvis dominated from 0% to the peak CRP, while the trunk took over from the peak CRP to 100% during the acceleration phase. The mean CRP showed a moderate to large negative correlated (Table. 1) with racket speed suggests that players with the fastest racket speeds tend to exhibit a greater pelvis-trunk separation angle and a longer backswing distance under simple task constraints. This phenomenon aligns with the principle of the stretch-shortening cycle, where active muscles generate a powerful force during the acceleration phase through concentric shortening when immediately preceded by counter rotation, revered by an eccentric muscle action[35,36]. Additionally, the correlation coefficient for peak CRP on the non-dominant side (r = 0.488, Table. 1) likely highlights the importance of precise timing between the stretching and shortening phases in maintaining robust racket speed during non-dominant pelvis-trunk coordination[10,37]. These findings underscore the critical role of non-dominant pelvis-trunk coupling in generating racket speed under lower task constraints. This observation supports prior research emphasizing the non-dominant side's contribution to racket speed

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At the medium movement distance, the increase in the number of coordination features showed a
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The current study had several limitations. In terms of the study population, the selection of skilled male athletes was limited to the one college. In addition, racket speed likely distortions by data smoothing at the moment of impact. When interpreting the results of this study, it is important to acknowledge that pelvis-trunk coordination represents just one component of the complex movements involved in the tennis forehand. This study specifically focused on task constraints and did not consider potential interactions with other factors, such as self-organizing and environment elements (e.g., unanticipated situations, fatigue). Given the dynamic nature of tennis, it is reasonable to hypothesize that the ability to adapt to unanticipated scenarios and the physiological and psychological fatigue associated with match play could influence pelvis-trunk coordination and its relationship to performance. Individual variability in player strategies was not considered in many of the analyzed variables. The decision not to evaluate players individually was made to identify broader trends in pelvis-trunk coordination during forehand strokes, rather than focusing on specific strategies. However, individual differences may play a critical role in performance outcomes. Future research should investigate whether individual coordination patterns are linked to performance metrics, such as racket speed, to deepen our understanding of how specific biomechanical factors contribute to optimal performance.

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Conclusions

This study highlights the complex relationship between pelvis-trunk coordination and racket speed during tennis forehand strokes across varying movement distances. While racket speed remained consistent across movement distances, significant variations in pelvis-trunk coordination were observed, particularly during the acceleration phase. These variations were influenced by movement distance, with distinct coordination features correlating with racket speed at each distance. These findings emphasize the dynamic nature of coordination strategies in response to varying task
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These findings emphasize the dynamic nature of coordination strategies in response to varying task constraints and underscore the importance of core muscle activation for effective pelvis-trunk coupling. The results also revealed that coordination variability increased with task demands, suggesting that players require greater neuromuscular flexibility to maintain optimal performance at higher movement distances. Furthermore, this study supports the notion that developing flexibility and coordination in both non-dominant and dominant pelvis-trunk movements is essential for maximizing racket speed. Coaches and players should focus on improving coordination strategies that can be applied across different movement distances to optimize performance. Future research should investigate the impact of individual differences in coordination patterns and their relationship to performance, particularly under the complex and unpredictable conditions encountered during match play.

Key points

- Movement Distance Influences Pelvis-Trunk Coordination: Significant changes in pelvis- trunk coordination were observed as movement distance increased in skilled male player, particularly during the pre- and post-acceleration phases, highlighting the adaptability of coordination strategies to varying task demands.

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- Correlation Between Coordination Features and Racket Speed: Key coordination features, such as mean and peak CRP values, were significantly correlated with racket speed at different movement distances, emphasizing the role of pelvis-trunk coupling in generating higher racket speeds.

- Confirmed Previous Reports of Increased Coordination Variability: As movement distance increased, greater variability in pelvis-trunk coordination was observed in skilled male player, indicating the necessity of greater flexibility and neuromuscular strategies to sustain performance under higher task constraints.

- Non-Dominant Peak CRP tended to be associated with faster Racket Speed: Non-dominant side coordination, particularly the rotational speed of the trunk relative to the pelvis in transverse plane, was tended to be associated with faster racket speeds, especially under lower task constraints.

Acknowledgments

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Figure Captions

Figure 1. Set up description: (a) marker spot position; (b) experiment environment simulation. The black dotted line represents the maximum movement distance; the green dotted line represents the medium movement distance; the red dotted line represents the minimum movement distance; and the arrow represents the move direction

Figure 2. Non-dominant and dominant pelvis-trunk continuous relative phase (CRP) curves and standard deviations in different movement distances during the acceleration phase; the black bar represents the time and SPM statistics results during which the differences occurred

Figure 3. Mean and standard deviation of the continuous relative phase (CRP) curves of the nine participants with the fastest racket speed (solid line) and the other nine participants with the slowest racket speed (dashed line) at different movement distances