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Section I – Kinesiology

Adaptive Forehand Stroke Strategies for Varying Ball Speed in Tennis Performance

by

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In this study, we examined multiple hypotheses concerning the variations in tennis forehand strokes contingent on the velocity of the incoming ball and the player's proficiency. The experiment involved seven expert tennis players and six novice players, who were tasked with striking a ball projected from a ball machine under three randomized speed conditions: slow (mean ± SD: 7.54 ± 0.65 m/s), medium (10.83 ± 0.59 m/s), and fast (14.42 ± 0.50 m/s). Participants were instructed to execute a forehand drive toward the ball machine as accurately as possible while exerting maximum effort, without compromising accuracy. A motion capture system equipped with eight infrared cameras was employed to measure reflective markers affixed to the subjects' bodies and rackets. The objective of this study was to analyze the angular motion of each segment involved in the forehand stroke in the transverse plane, with a particular focus on angular displacement and maximum angular velocity. Furthermore, a comparison was made of the synergy indices computed from the segment angles at impact. The results indicated a decline in angular displacement with increasing ball speed, consistent with the hypothesis. In comparison with the novice group, the expert group demonstrated significantly greater usage of the distal segment with a decoupling strategy, as well as proper adjustments of other segments, particularly the trunk, depending on ball speed. The synergy index exhibited an increase with increasing ball speed; however, no significant difference was observed between the two groups.

***Keywords**: motion capture; multi-joint coordination; uncontrolled manifold hypothesis; cluster analysis; expert; novice*

Introduction

It is imperative to acknowledge the pivotal role of the forehand drive stroke in modern tennis performance. The quality of the forehand drive, which encompasses aspects such as accuracy, speed, and spin of the ball, has been observed to have a substantial impact on the outcome of a match, often determining the winner. Kinematic analysis through motion capture has emerged as a prevalent analytical tool in sports performance, with prior studies examining the forehand drive (Genevois et al., 2020; Kawamoto et al., 2024; Reid et al., 2013). Given the heterogeneity in incoming balls and forehand swing types, delineating the optimal forehand drive (i.e., time sequence of posture) can be a formidable task. In essence, the most critical factor for successful performance and the potential analytical focus to distinguish the performance between expert and novice players is the proper behavioral response, that is, the joint configuration with proper muscle activation involved in the task, to unpredictable incoming ball properties, e.g., speed, direction, spin, etc.

In contrast to sports skills such as baseball

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pitching, golf and tennis serves, where the ball is stationary or shows minimal variation across attempts, allowing for an ideal swing, the forehand drive of tennis requires the player to adjust their swing to each incoming ball. It is first necessary for the players to perceive the state of the ball that is approaching, and subsequently select an appropriate prearranged swing. They should also continuously track the ball's position in real time to ensure spatiotemporal accuracy at impact, which is described by the control model of perceptuomotor and preprogrammed control (Dessing et al., 2002; Tresilian, 2005). The range of incoming ball speeds in tennis is far more diverse than in many other sports motions. The present study thus focused on the change of the forehand drive swing in response to different incoming ball speeds. Many movements like throwing or striking are sequenced in a proximal to distal pattern to get mechanical and biological advantages (Serrien and Baeyens, 2017). The forehand drive is also highly associated with proximal to distal sequence (Landlinger et al., 2010). The forehand drive is comprised of multiple segments (i.e., trunk, arm, and hand), and the movements of each segment must be meticulously coordinated. Consequently, an examination of how each segment responds to ball speed is necessary to gain a more profound understanding of the forehand drive's responsiveness to incoming balls of varying speeds.

As mentioned above, multiple segments work together to produce racket movement, illustrating a redundant system in which the degrees of freedom (DoF) of the elements exceed the task level DoF. Given this redundancy, the variability of the element variables is higher than the variability of the performance variable. However, previous studies have investigated that the central nervous system utilizes the variability of element variables to stabilize performance variables, as described by the Uncontrolled Manifold (UCM) hypothesis. This stabilization can be understood as system stability, which can be influenced by various factors such as fatigue, age, and training (Park et al., 2015; Scholz et al., 2000; Shim et al., 2004; Singh et al., 2012).

Quantifying the quality of the forehand drive and establishing a standard for an ideal swing is subjective. As a result, previous studies have employed an expert versus novice framework for biomechanical analysis (Blackwell et al., 1994; Lambrich and Muehlbauer, 2023), hypothesizing that the swing of the expert group exhibits higher quality. Beyond the biomechanical aspects of the swing itself, previous research has shown that expert players' anticipations of their opponents' stroke directions were faster and more accurate than those of novice players (Del Villar et al., 2007). Therefore, this study also aimed to highlight differences in the ability to adjust swing strategies according to situational demands, using the expert vs. novice concept as a framework.

Thus, the current study aimed to investigate how the upper body segments would respond to ball speed and to examine how this response would vary with experience or the skill level. We analyzed kinematic variables describing the movement of each segment and the variability in the movements of selected segments across trials to test the following hypotheses: (1) the expert group would utilize the distal segments more actively than the novice group regardless of ball speed; (2) the magnitude of the segmental movement would be reduced as the ball's speed increased to guarantee an accurate impact; (3) the tendency to adjust swing strategies according to ball speed would be more prominent in the expert group than in the novice group; (4) stabilization of the racket angle by utilizing variability in the upper body configuration (e.g., angles of the trunk, the arm, and the hand) would be greater in the expert group than in the novice group.

Methods

Participants

The study's participants comprised two groups: seven professional college players (expert: age: 22 ± 1.9 years; body height: 1.78 ± 0.05 m; training experience: 10 ± 2 years, mean ± SD) and six novice players (novice: age: 28 ± 5.1 years; body height: 1.76 ± 0.04 m; training experience: 1.5 ± 0.8 years). Professional players were selected as an expert group due to their extensive experience (> 10 years). Novice players in this study had engaged in regular tennis play for less than three years. The expert group participants were all members of the varsity team at the university, and the experiment was conducted after the competitive season was over. During that season, players achieved three championships, one second-place finish, and four third-place finishes in four major domestic

competitions in South Korea. In the team competitions, they also achieved one runner-up position. All participants were male, right-handed and had no history of muscular or neurological disorder. The experiments for this research were conducted after obtaining approval from the institutional review board of the Seoul National University, Seoul, South Korea (approval code: 2112/002-020: approval date: 13 December 2021).

Measures

All experiments were conducted within the confines of an indoor tennis court. This approach was taken to avoid any potential unintended effects on the participants' performance that might be caused by environmental factors such as wind or temperature. The configuration of the experimental setup and equipment is depicted in Figure 1. A motion capture system comprising eight infrared cameras (Oqus 500, Qualisys, Sweden) was employed at a sampling rate of 150 Hz. On one side of the court, a delineated area along the baseline demarcated the position at which participants would execute their strokes, with the infrared cameras positioned circumferentially around this area. Participants wore a tight-fitting suit during the experiment, which facilitated the attachment of 16 markers (20 mm in diameter) to their bodies, including the head, both sides of the acromion, the elbow, the wrist, and the hand. Four additional markers were placed on the tennis racket, specifically at the 3, 6, 9, 12 o'clock positions on the racket head. A ball machine, capable of adjusting both the projection angle and speed, was positioned at the center of the baseline on the opposite side of the participant to project the balls.

Design and Procedures

Experimental Setup

The ball machine was configured to project tennis balls at three distinct speeds: slow (mean ± SD: 7.54 ± 0.65 m/s), medium (mean ± SD: 10.83 ± 0.59 m/s), and fast (mean ± SD: 14.42 ± 0.50 m/s). These speeds were determined through a pilot test and interview to ensure that participants could perceive the differences in ball speed. Prior to the experiment, participants were permitted to hit the ball more than ten times as a practice session at each speed to familiarize themselves with the ball speeds and the experimental environment for about 10 min. The actual data acquisition began when participants gave a signal saying "no more practice necessary" and the ball machine was tested and confirmed to launch the ball at programmed speeds (1–2 min).

Experimental Procedure

Each participant completed four blocks of tasks, with each block comprising 15 trials. Consequently, the total number of trials administered to each participant was 60. Within each block, 15 trials were allocated to each of the three ball speeds, with five attempts designed for each ball speed (3 × 5 = 15 trials). It is noteworthy that the ball speeds of the 15 trials within each block were fully randomized; thus, participants were unaware of the ball speed information prior to the release of the balls. Participants were instructed to hit the ball at their waist level using the forehand drive toward the ball machine as accurately as possible and with maximum effort, without compromising accuracy. To encourage the adoption of their natural strategy and ensure comfort, all participants were permitted to utilize their own racket.

Data Analysis

The recorded three-dimensional (3D) marker position data were filtered using a zero-lag, fourth-order low-pass Butterworth filter with a cutoff frequency of 6 Hz which has been widely used in biomechanical and sports analyses (Rácz and Kiss, 2021; Song et al., 2023; Vial et al., 2020). The filtered kinematic data were then exported to Visual3D software to define joint center coordinates, including the shoulder, elbow, and wrist joints. For this study, we analyzed a three-segment chain consisting of the trunk, the arm, and the hand. Our focus was to examine the angular motion of each segment of the forehand stroke observed in the *transverse plane*. To accomplish this, joint positions were projected onto the transverse plane to define each segment (Landlinger et al., 2010; Reid and Elliott, 2002). The trunk segment was defined as the line connecting both shoulders, the arm segment was defined as the line from the shoulder to the wrist, and the hand segment was defined as the line from the wrist to the marker on the third metacarpophalangeal joint. The trunk and racket angles were calculated as absolute

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angles in the global reference coordinates, while the arm and hand angles were assessed as relative local angles with respect to their proximal segments (Elliott et al., 1989; Zheng et al., 2008).

Joint Angles: Angular Displacement & Maximal Angular Velocity

The forehand stroke is typically divided into two phases, the back swing and the forward swing. Players are supposed to accelerate the racket prior to impact in order to execute a more powerful shot, necessitating a swing back to secure the space where the racket can be accelerated during the forward swing. In this study, the forward swing phase was analyzed, with its start and end (i.e., the time moment of ball impact) defined as follows: the time moment of the ball impact was identified in the time-series kinematic data as the point at which the markers on the racket exhibited the highest acceleration (Busuttil et al., 2022). The onset of the forward swing for each segment was determined as the moment when the angular velocity of that segment reached 5% of its maximum angular velocity occurring prior to impact (Yang and Scholz, 2005). For each segment, the angular displacement between the moment of impact and the onset of the forward swing, as well as the maximum angular velocity during the forward swing, were the focus of the analysis. The variables of angular displacement, maximum angular velocity determined from each trial were averaged for each speed condition and used in subsequent statistical analysis.

Cluster Analysis: Silhouette Coefficient

The silhouette coefficient was calculated to assess data clustering, with this coefficient generally evaluating how well data points within each condition were grouped and how clearly these clusters were distinguished from one another (Vitali et al., 2019; Watari et al., 2021). In this study, a high silhouette coefficient signified that the data points were well-clustered within each speed condition and that each cluster was distinctly separated from clusters under other speed conditions. The data used in the analysis encompassed two dimensions: one denoting the racket's maximum angular velocity and the other representing the maximum angular velocities of individual segments, such as the trunk, the arm, and the hand, which influenced the racket's movement (Figure 4A & 4B). For each plotted data point, the distance to other points within the same cluster was calculated, as shown in Equation 1. A smaller distance indicated a more tightly clustered data set.

$$s(i) = \frac{b(i) - a(i)}{\max\{a(i), b(i)\}} \qquad (1),$$

where $a(i)$ was the mean distance between a sample (i) and all other points in the same class, and $b(i)$ stood for the mean distance between a sample (i) and all other points in the nearest cluster. The silhouette coefficient for the entire dataset was then computed as the average of $s(i)$ values across all samples, as shown in Equation 2.

$$Silhouette\ coefficient = \frac{\sum_{i=1}^{n} s(i)}{n} \qquad (2),$$

An overall silhouette coefficient that approached 1 indicated that data points were well-clustered within each ball speed condition and were distinctly separated from clusters of other speed conditions. Conversely, values that approach −1 suggested overlapping or poorly defined clusters between speed conditions.

Co-Variation Pattern & Two Components of Variances of Multi-Joint Angles

The uncontrolled manifold (UCM) analysis examines the patterns of the variances in redundant elemental variables (EVs) across repeated trials that channel into the subspace spanned by the null space vectors of the Jacobian matrix (i.e., uncontrolled manifold space, UCM space) and the orthogonal complement to it (ORT space). In instances where the component of variance along the UCM space is comparatively larger than that along the ORT space, then, it is highly probable that the data distribution is organized in a manner that prioritizes the stabilization of the salient performance variable (PV) (Latash et al., 2002; Scholz et al., 2000). In order to maintain a consistent direction of the ball during repetitive forehand strokes, it was essential to stabilize the racket orientation. This could be accomplished through proper configurations of the trunk, the arm, and the hand, which are referred to as solution families. In this analysis, the racket orientation was designated as the salient PV, while the trunk, arm, and hand angles were set to the EVs. The Jacobian, which represented the linear relationship between small changes in the EVs and changes in the PV, was set to [1; 1; 1]. Subsequently, the magnitude of variance along the UCM and

ORT spaces (i.e., V_{UCM} and V_{ORT}) was calculated as a dependent variable using the following equations:

$$V_{UCM} = \frac{\sum_{trials} \theta_{UCM}{}^2}{(m-d) \cdot N_{trials}} \quad (3),$$

$$V_{ORT} = \frac{\sum_{trials} \theta_{ORT}{}^2}{d \cdot N_{trials}} \quad (4),$$

$$\Delta V = \frac{V_{UCM} - V_{ORT}}{[V_{UCM} \cdot (m-d) + V_{ORT} \cdot d]/m} \quad (5),$$

where $\theta_{UCM}{}^2$ and $\theta_{ORT}{}^2$ were calculated as squared length of the deviation vector lying within the UCM and ORT spaces, respectively; m and d stood for the number of dimensions of EVs and PV, respectively; N_{trials} was the number of the valid strikes; ΔV was log-transformed using the Fisher transformation.

Statistical Analysis

All data are presented as means with standard errors. The formulated hypotheses were related to identifying differences in the kinematic patterns of upper body segments, including the racket, during the forehand stroke as influenced by ball speed and tennis expertise. To test this, a set of dependent variables—angular displacement, maximum angular velocity, V_{UCM}, and V_{ORT}—were analyzed using a mixed-design two-way repeated measures (RM) ANOVA, with factors of *Group* (two levels: expert and novice) and *Speed* (three levels: slow, medium, and fast). The Mauchly's sphericity test was used to confirm the assumption of sphericity, and the Greenhouse-Geisser correction was applied when this assumption was violated. For significant factor interactions, post-hoc analyses included one-way RM ANOVA for comparisons across speed conditions and independent *t*-tests for group comparisons.

We further investigated the relationship between the maximum angular velocity of the racket and each upper body segment. Linear regression analysis was conducted separately for each participant by pooling data across all trials and ball speed conditions. All statistical analyses were conducted using SPSS (version 25; IBM, Armonk, NY, USA).

Lastly, the statistical power for all comparisons was estimated, thereby confirming that the power of all planned comparisons was about 0.7 for the pool of 13 participants in the two groups. Furthermore, the effect sizes, partial eta squared (ηp^2), and Cohen's *d*, were reported for all the presented results. Specifically, partial eta squared (ηp^2) was employed for ANOVA tests, while Cohen's *d* was used for *t*-tests. The interpretation of effect sizes followed established criteria: partial eta squared, values around 0.01, 0.06, and 0.14 were classified as small, medium, and large, respectively (Richardson, 2011); for Cohen's *d*, absolute values around 0.2, 0.5, and 0.8 were considered as small, medium, and large (Cohen, 2013). The statistical significance was set at $p < 0.05$.

Results

Angular Displacement

The findings revealed a consistent pattern of angular displacement for both the racket (Figure 3A) and the trunk (Figure 3B) across different speed conditions. Notably, there was no significant difference observed between the expert and novice groups. These results were further substantiated by the mixed-design two-way RM ANOVAs, incorporating the factors of *Group* and *Speed*. This analysis revealed a substantial main effect of *Speed* on both the racket and the trunk, with the former exhibiting a significant decrease in angular displacement with increasing speed (racket: $F_{[1.095, 12.046]} = 21.446$, $p < 0.001$, $\eta p^2 = 0.661$; trunk: $F_{[1.263, 13.892]} = 62.745$, $p < 0.001$, $\eta p^2 = 0.851$) without factor interaction.

The angular displacement of the arm (Figure 3C) and the hand (Figure 3D) differed based on the expertise level, with the expert group demonstrating larger angular displacements than the novice group. Additionally, the angular displacement of the hand decreased significantly with increasing ball speed in both the expert and novice groups. These results were confirmed by a significant main effect of *Group* (arm: $F_{[1, 11]} = 5.635$, $p = 0.037$, $\eta p^2 = 0.339$; hand: $F_{[1, 11]} = 5.835$, $p = 0.034$, $\eta p^2 = 0.347$) and *Speed* (hand: $F_{[1.275, 14.023]} = 49.052$, $p < 0.001$, $\eta p^2 = 0.817$) without factor interaction.

Maximum Angular Velocity

The expert group exhibited a higher maximum angular velocity of the racket compared to the novice group and reduced this maximum velocity as ball speed increased. This pattern was not observed in the novice group (Figure 4A). These results were confirmed by a significant main effect of *Group* ($F_{[1, 11]} = 7.532$, $p = 0.019$, $\eta p^2 = 0.406$)

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and *Speed* ($F_{[1.271, 13.981]}$ = 4.62, p = 0.042, ηp^2 = 0.296) with factor interaction ($F_{[1.271, 13.981]}$ = 5.226, p = 0.032, ηp^2 = 0.322). Post-hoc pairwise comparisons revealed that the expert group showed a larger maximum angular velocity of the racket than the novice group under slow and medium ball speed conditions (slow: p = 0.03, Cohen's d = 1.913; medium: p = 0.013, Cohen's d = 1.433). Additionally, within the expert group, maximum angular velocity differed by ball speed, with slow ≈ medium > fast (p < 0.05; ηp^2 = 0.586).

For the trunk's maximum angular velocity (Figure 4B), only the expert group exhibited a pattern of decreasing angular velocity with increasing ball speed. It was confirmed by a main effect of *Speed* ($F_{[2, 22]}$ = 21.919, p < 0.001, $\eta p2$ = 0.666) and *Speed* × *Group* interaction ($F_{[2, 22]}$ = 9.16, p = 0.001, ηp^2 = 0.454). The significant factor interaction implied that the different angular velocity of the trunk between groups was present only under slow and medium conditions (expert > novice; slow: p = 0.019, Cohen's d = 1.307; medium: p = 0.036, Cohen's d = 1.109), and the expert group showed different angular velocity with slow > medium > fast (p < 0.05, ηp^2 = 0.884).

In contrast to the trunk, the maximum angular velocity of the arm (Figure 4C) had a trend to increase with ball speed increment. Only a significant main effect of *Speed* was observed ($F_{[2, 22]}$ = 10.249, p < 0.001, ηp^2 = 0.482).

For the hand (Figure 4D), there was no difference in maximum angular velocity according to ball speed in both groups. However, the expert group exhibited a higher maximum angular velocity than the novice group, which was confirmed by a significant main effect of *Group* ($F_{[1, 11]}$ = 6.659, p = 0.026, ηp^2 = 0.377), without factor interaction.

Correlation between Maximum Angular Velocity of the Racket and Other Segments

As illustrated in Table 1, a correlation analysis was conducted to examine the relationship between the maximum angular velocity of the racket and other segments. The values presented in the table correspond to the R values from the correlation analysis, with asterisks denoting p values for each corresponding correlation. It is noteworthy that some R values were negative, yet none of them were statistically significant. In turn, for both groups, the maximum angular velocities of each segment were positively correlated with the maximum angular velocity of the racket.

Silhouette Coefficient

The silhouette coefficient between the trunk and the individual segmental angular velocity for each participant is presented in Table 2. The majority of participants in the expert group, with the exception of one, exhibited positive values, whereas all participants in the novice group demonstrated negative values. Furthermore, Figure 5 presents scatter plots with racket maximum angular velocity on the x-axis and trunk maximum angular velocity on the y-axis. This figure illustrates data for representative participants from the expert group (Figure 5B) and the novice group (Figure 5A), respectively.

Synergy Indices & Two Components of Variance in Multi-Joint Angles

Both groups showed a trend of increasing V_{UCM} with higher ball speeds, with the novice group exhibiting larger V_{UCM} than the expert group (Figure 6A). These results were supported by the mixed-design two-way RM ANOVAs with factors of *Group* and *Speed*, which showed a significant main effect of *Group* ($F_{[1, 11]}$ = 7.389, p = 0.02, ηp^2 = 0.402) and *Speed* ($F_{[2, 22]}$ = 18.532, p < 0.001, ηp^2 = 0.628) with factor interaction ($F_{[2, 22]}$ = 5.285, p = 0.013, ηp^2 = 0.325). Post-hoc analysis for the interaction effect revealed that V_{UCM} in the expert group was significantly lower than in the novice group only under the fast ball condition (p < 0.001, Cohen's d = 2.892). Additionally, significant differences in V_{UCM} across ball speed conditions were observed, with slow < fast in the expert group (p < 0.05, ηp^2 = 0.586), and slow ≈ medium < fast in the novice group (p < 0.05, ηp^2 = 0.714).

For V_{ORT} (Figure 6B), the novice group showed higher values than the expert group. No differences were observed across speed conditions in the expert group, whereas the novice group showed an increase in V_{ORT} with faster ball speeds. These results were confirmed by significant main effects of *Group* ($F_{[1, 11]}$ = 6.782, p = 0.025, ηp^2 = 0.381) and *Speed* ($F_{[2, 22]}$ = 7.033, p = 0.004, ηp^2 = 0.39) with factor interaction ($F_{[2, 22]}$ = 4.022, p = 0.032, ηp^2 = 0.268). Pairwise comparisons between the two groups under each speed condition revealed that the novice group had significantly larger V_{ORT} than

the expert group at the fast speed condition ($p < 0.05$, Cohen's $d = 2.075$). Furthermore, within the novice group, the V_{ORT} under the fast condition was significantly greater than under the slow condition ($p < 0.05$, $\eta p^2 = 0.525$). The ΔV showed an increasing trend as ball speed increased, yet no significant difference between groups. These results were confirmed by the main effect of *Speed* ($F_{[2, 22]} = 4.39$, $p < 0.05$, $\eta p^2 = 0.285$; Figure 6C).

Table 1. Correlation analysis between maximum angular velocity of the racket and other segments.

Group	Subject	*R*		
		Racket-Trunk	Racket-Arm	Racket-Hand
Expert	Sub1	0.626***	0.302*	0.936***
	Sub2	0.526***	−0.239	0.923***
	Sub3	−0.014	0.317*	0.926***
	Sub4	0.428**	0.535***	0.929***
	Sub5	0.710***	0.311*	0.905***
	Sub6	0.478**	0.112	0.838***
	Sub7	0.659***	0.760***	0.980***
Novice	Sub1	0.513***	−0.221	0.920***
	Sub2	0.500**	0.417*	0.620***
	Sub3	0.328*	0.714***	0.937***
	Sub4	0.535***	0.774***	0.599***
	Sub5	0.035	0.535***	0.934***
	Sub6	0.618***	−0.026	0.779***

One asterisk (*) indicates p < 0.05, two asterisks (**) indicate p < 0.01, and three asterisks (***) indicate p < 0.001

Table 2. Silhouette coefficient of within-subject.

Group	Subject	**Silhouette Coefficient**		
		Racket-Trunk	Racket-Arm	Racket-Hand
Expert	Sub01	**0.035**	**0.177**	**0.040**
	Sub02	**0.118**	**0.174**	**0.073**
	Sub03	−0.070	**0.250**	−0.062
	Sub04	**0.038**	**0.054**	−0.093
	Sub05	**0.202**	**0.157**	**0.238**
	Sub06	**0.175**	**0.290**	**0.281**
	Sub07	**0.218**	**0.199**	**0.224**
Novice	Sub01	−0.050	**0.029**	−0.072
	Sub02	−0.080	−0.033	−0.076
	Sub03	−0.113	−0.099	−0.149
	Sub04	−0.067	**0.115**	**0.077**
	Sub05	−0.153	**0.058**	−0.180
	Sub06	−0.063	**0.048**	**0.042**

Positive silhouette coefficients are indicated in bold

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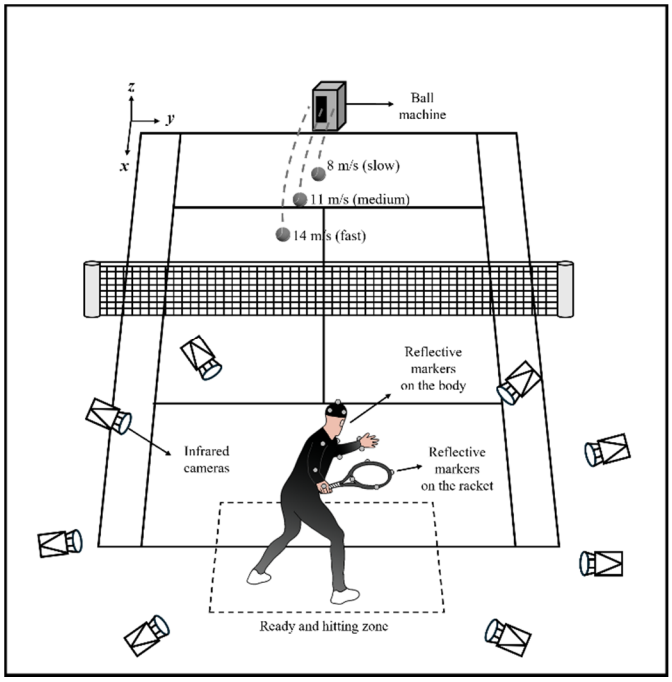

Figure 1. The illustration of the experimental environment. Subjects were ready for the balls behind the baseline. The ball machine placed at the center of the baseline projected the balls along the x axis.

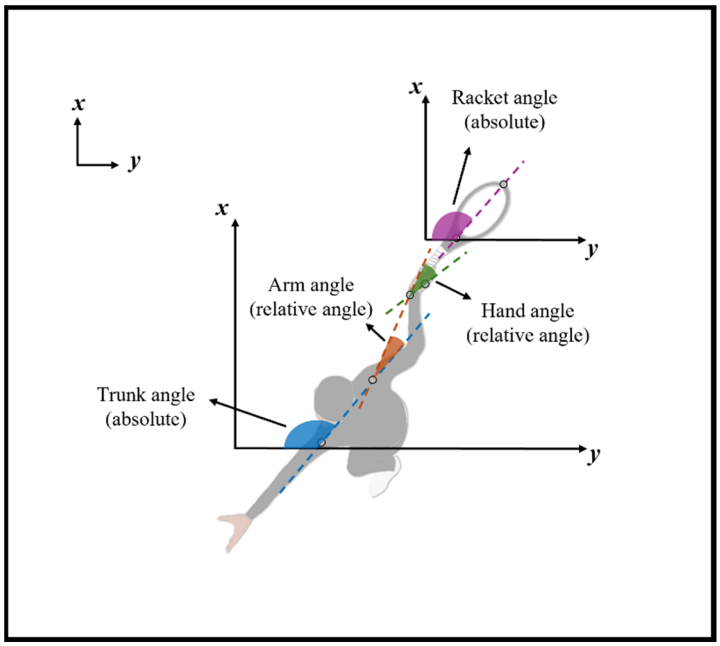

Figure 2. Schematic representation of the segment angles analyzed in this paper. Absolute angles (racket and trunk) were measured with respect to the global coordinate system, while relative angles (arm and hand) were measured with respect to the more proximal segment.

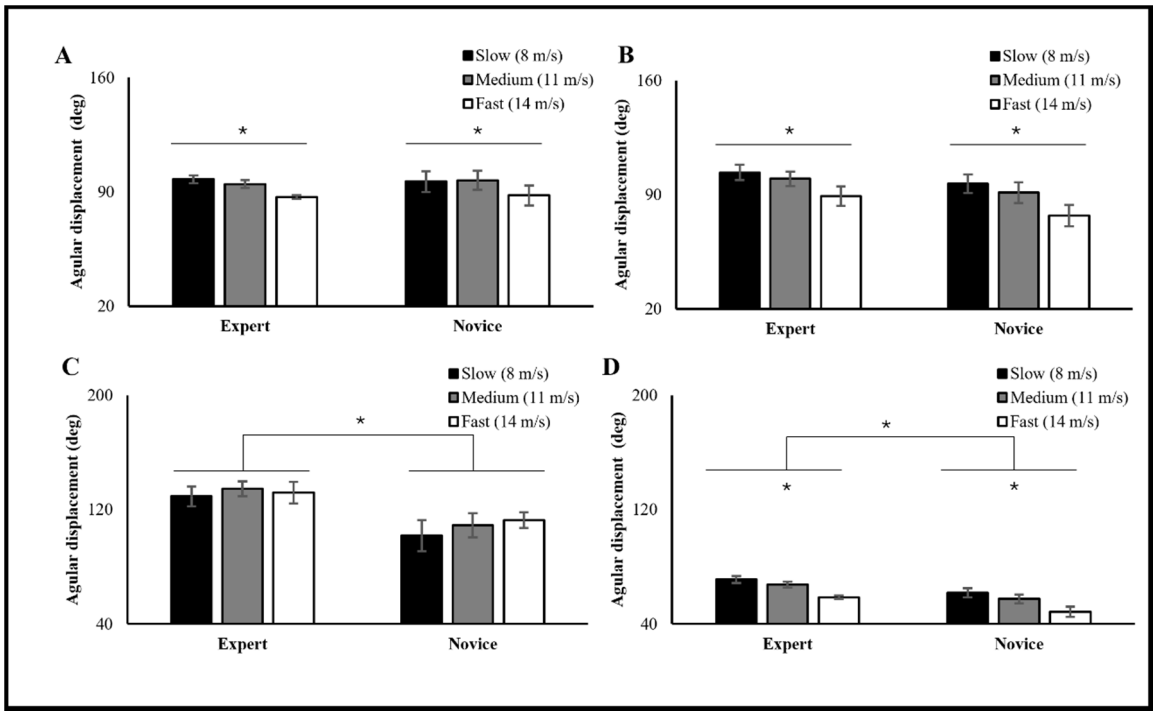

Figure 3. Average values of angular displacement of segments for both groups and all speed conditions: (A) racket, (B) trunk, (C) arm, and (D) hand. The error bars are SE, and the asterisks indicate significant differences between conditions ($p < 0.05$).

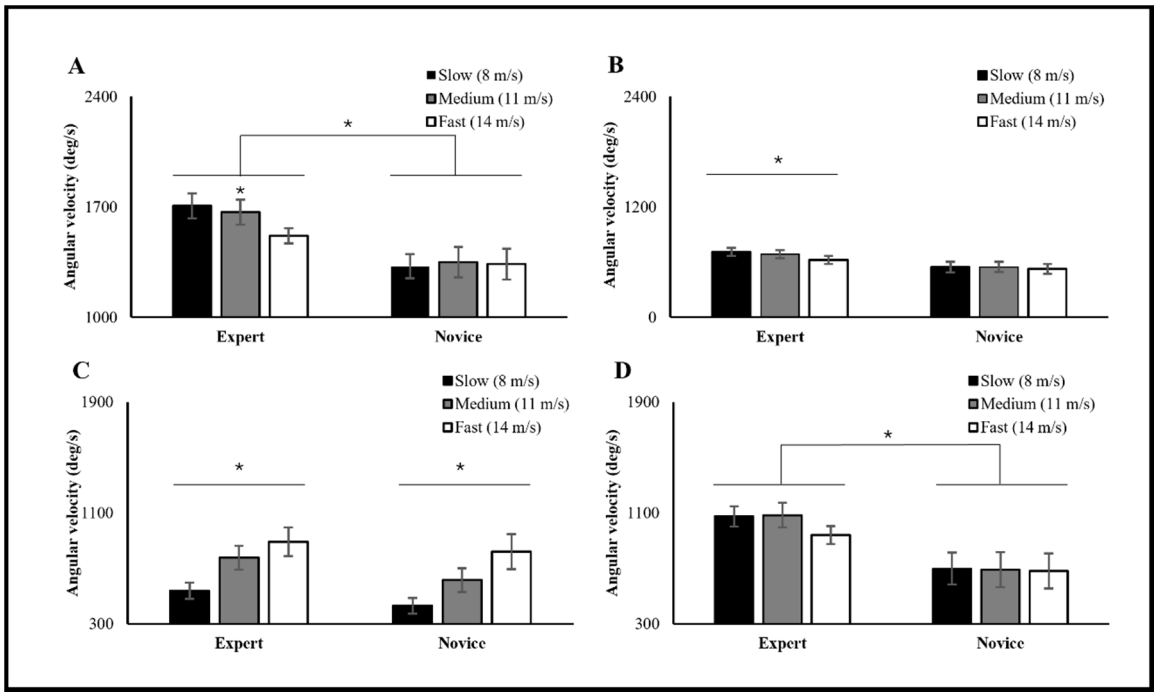

Figure 4. Average values of maximum angular velocity of segments for both groups and all speed conditions: (A) racket, (B) trunk, (C) arm, and (D) hand. The error bars are SE, and the asterisks indicate significant differences between conditions ($p < 0.05$).

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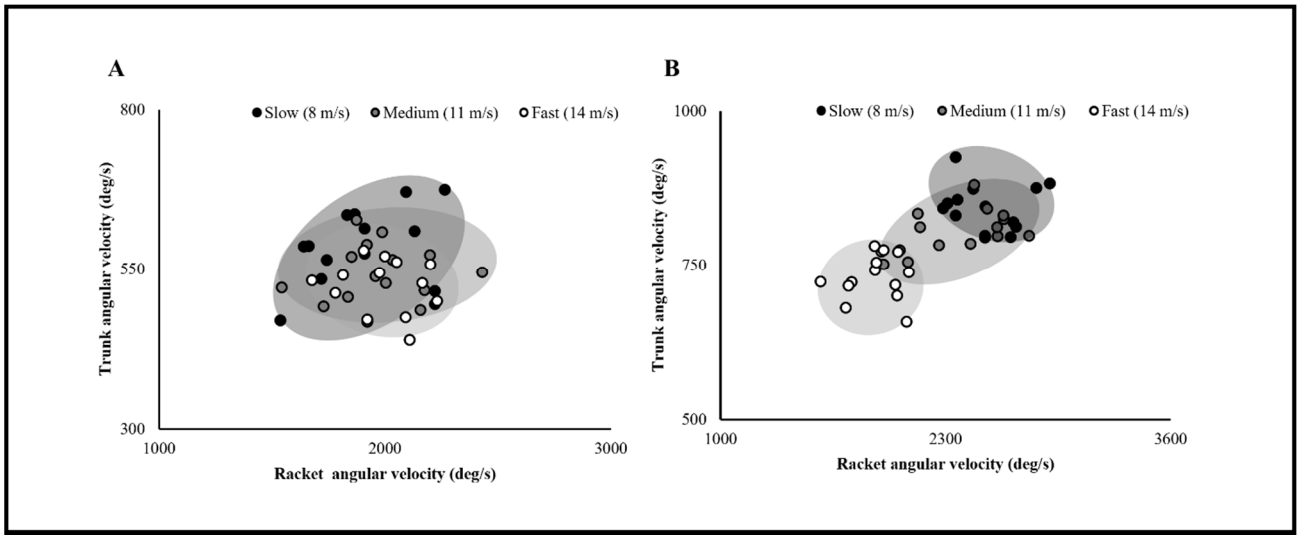

Figure 5. The scatter plot showing the relationship between maximum angular velocity of the racket and the trunk. The scatter plot of the representative participants for each group is presented: (A) novice, (B) expert. Circles represent the 95% confidence interval for each speed condition.

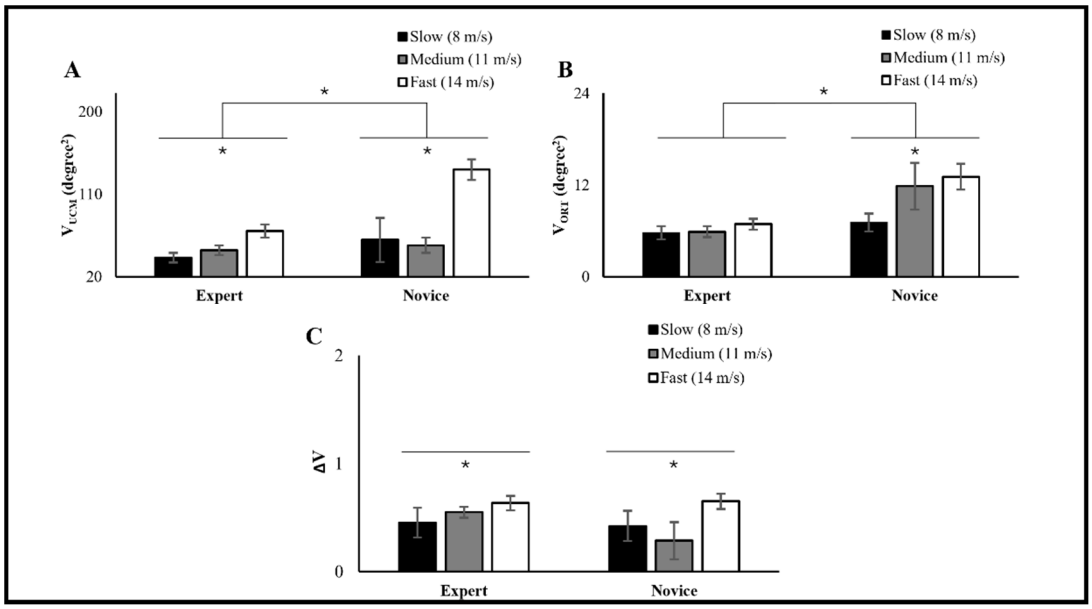

Figure 6. Average values of variance per degree of freedom for both groups and all speed conditions: (A) V_{UCM}, (B) V_{ORT}, and (C) ΔV. The error bars are SE, and the asterisks indicate significant differences between conditions ($p < 0.05$).

Discussion

In this study, participants were instructed to strike balls toward the ball machine, potentially necessitating adjustment to the proximal to distal sequence patterns based on the ball speed to ensure accurate impact. The results obtained in this study confirmed hypotheses 1, 2, and 3. These hypotheses were supported by the results, which showed that the experts demonstrated a significant usage of the distal segment with proper adjustment of the other segments depending on the ball speed, more evidently than the novice group. However, the experimental findings did not support the fourth hypothesis, which predicted a group difference in coordination indices, i.e., synergy indices, for the stabilization of the racket orientation. The subsequent discussion will focus on the common behavioral aspects and distinguishable behavioral patterns between the two groups in response to increasing ball speed.

Common Strategy in Response to Ball Speed: Negative Relationship between Angular Displacement and Ball Speed

For both the expert and novice groups, the angular displacement of the segments exhibited a negative correlation with increasing ball speed, a finding that aligns with the conclusions of previous research (Gray, 2002). This finding suggests that a negative relationship between the swing range, i.e., angular displacement, and the ball speed would be a common strategy irrespective of the skill level. However, the underlying advantage of this strategy remains to be elucidated. We have to admit that the current data set was insufficient to provide a definitive answer to this question. Given the multifaceted nature of factors influencing speed and range of motion, including mechanical, physiological, and neural elements, further research is necessary to ascertain the specific contributions of these factors to the observed phenomenon. The most evident physical rationale pertains to the objective of minimizing the required time to move the racket to the precise impact position. Another possibility was to increase the stiffness of the joint while reducing the range of motion by the co-activation of agonist and antagonist muscles, which would result in a stable joint configuration and might enhance the accuracy of the performance.

A notable finding supported by the current results was that the maximum angular velocity of the arm increased in proportion to the increase in ball speed. This can be interpreted as a compensatory strategy employed by participants in both groups to mitigate the decrease in usage of other segments. This is due to the necessity of both accurate impact and sufficient energy within the racket to strike the ball towards the target. This strategy can be conceptualized as a method of ensuring that the segments responsible for generating sufficient kinetic energy are not impeded by the ball.

Coupled and Decoupled Actions of the Proximal and Distal Segments in the Expert Group

Given the serial linkage between the arm, the hand, and the racket, the contribution of the arm and the hand, such as angular velocity, can be transferred (coupled) to the racket movements. Compared to the novice group, the strategies of the expert group were to achieve relatively higher maximum angular velocity of the hand, leading to a higher maximum angular velocity of the racket. This finding can be interpreted as evidence of effective coupling between the maximum angular velocities of the hand and those of the racket. Furthermore, this result is substantiated by a robust positive correlation between maximum angular velocities of the racket and the hand, as shown in Table 1.

To achieve higher maximum angular velocity, securing a longer acceleration phase is advantageous. The significant group difference in the angular displacement of the arm and the hand (expert > novice) can be understood as the expert group employed a strategy that utilized the acceleration phase more effectively than the novice group. Despite these pronounced differences, the angular displacement of the racket exhibited no difference between the two groups. This finding indicates that, in addition to anatomically driven coupled actions, decoupled actions induced by the control scheme or the skill level play a critical role in determining the movement of the end-effector (i.e., the racket). Specifically, the expert group adjusted the displacement of the most distal part, the racket, which was not synchronized (decoupled) with the displacement of other segments (arm and hand). This decoupling was likely intentional, because an excessive racket movement resulting from the large movement of

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the proximal segments may lead to inaccurate striking (Hume et al., 2005).

Group Difference in Adaptive Strategy to Ball Speed

The expert group was able to adjust their maximum racket angular velocity according to ball speed, while the novice group was not. Notably, the expert group's lowest maximum racket angular velocity under the fast condition was still higher than the novice group's highest maximum angular velocity. This can be interpreted as the expert group not only achieved higher racket swing speeds but also had a greater range of speed options.

The scatter plots of the maximum angular velocities of the racket and the trunk of the representative participants from the two groups are presented in Figure 5A & 5B. Since the values that were compared in statistics were the average value across the trials, the silhouette coefficients were calculated to examine whether each participant adjusted to ball speed properly across multiple trials (Figure 5). According to Figure 5, the expert player's data points for each condition were well-clustered and distinguished from other clusters compared to the novice player. In accordance with the findings of the representative participants, it is evident that the majority of participants, with the exception of one, demonstrated a positive silhouette coefficient value (Table 2). This observation signifies that the racket and trunk maximum angular velocities exhibited effective control in alignment with the ball speed variables. However, it is noteworthy that all novice participants exhibited negative values, indicating a suboptimal adjustment of their racket and trunk maximum angular velocities in response to different ball speed conditions. This finding offers a potentially valuable insight for tennis players and their coaches, suggesting that adjusting trunk angular velocity to match the incoming ball speed may be a beneficial strategy for enhancing performance when facing fast balls.

Multi-Segmental Coordination: Ball-speed Dependency on the Composition of Variabilities

The concept of synergy (ΔV) is generally understood to signify the purposeful coordination or covariation between a redundant set of variables, with the objective being to ensure the stability of the salient performance variables given by the tasks (Kim et al., 2018) or the controller's preference (Zhang et al., 2008). In particular, trial-to-trial quantification of stability is employed to address flexible combinations of elements without compromising performance accuracy. In this regard, the present findings concerning the joint configuration in response to ball speed demonstrated that an increase in ball speed was associated with more flexible patterns of joint angle combinations. However, the fourth hypothesis regarding group differences in synergy indices was not substantiated.

From a computational perspective, the synergy index can be straightforwardly interpreted as the relative magnitude of two components of variance: V_{UCM} and V_{ORT}. Consequently, a substantial synergy index itself should not be a prerequisite for stable and accurate performance. In essence, the statistical analysis revealed that both V_{UCM} and V_{ORT} in the novice group exhibited greater magnitude compared to those in the expert group. This suggests that the more flexible patterns observed in the novice group were not necessarily indicative of more accurate performance.

Concluding Comments

The present study yielded significant findings regarding the disparity in forehand stroke strategies between expert and novice players, elucidated through the perspectives of biomechanics and motor control. Specifically, the expert group exhibited a distinct strategic difference from the novice group, characterized by proper segmental adjustment in conjunction with decoupled usage of the distal segment. Additionally, the expert group exhibited less flexible patterns (i.e., more consistent patterns) of segmental configuration with smaller error variance, contrasting with the patterns exhibited by the novice group. While the index of segmental coordination (synergy index) did not demonstrate a statistically significant difference between the two groups, the configuration of two sources of variance, V_{UCM} and V_{ORT}, exhibited clear distinctions between the groups.

Nevertheless, it is crucial to acknowledge the limitations of the present study. First, the study participants were recruited predominantly from the male demographic; second, the sample size

was rather modest, and finally, no metrics of the ball trajectory were recorded. Notwithstanding the aforementioned limitations, the statistical power for the majority of the variables and effect sizes was found to be within the acceptable range. However, it must be acknowledged that this does not guarantee that the current sample size is sufficient to draw definitive and straightforward conclusions regarding future implications. It is evident that the study findings are contingent on the replication of the experiment with a more substantial cohort of participants and the implementation of a more precise system for tracking the ball. Such an expansion would serve to substantiate the validity of the assumptions underlying the study findings, thereby ensuring their generalizability.

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