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Anticipatory COM-COP coordination as a determinant of forehand volley performance in skilled and non-skilled tennis players

BOYU SHEN[1], SU HANG[1], SHUAI WANG[1], ZHENGXIAO ZHANG[1,2], SUKWON KIM[1]

[1]Department of Physical Education, Jeonbuk National University, Jeonju, Republic of Korea; [2]College of Physical Education, Yichun University, Yichun, China.

Summary. The purpose of this study was to quantify how tennis players of different skill levels regulate their center of mass (COM) and center of pressure (COP) during forehand volleys, and to identify biomechanical strategies associated with stable and efficient performance. Sixteen right-handed players (8 skilled and 8 non-skilled) performed standardized forehand volleys while three-dimensional kinematics and ground reaction forces were recorded using a motion-capture system and force platforms. COM and COP trajectories (position, velocity, and acceleration) were extracted along the mediolateral, anteroposterior, and vertical axes and compared between groups using independent-samples t-tests. Skilled players exhibited substantially greater forward COM displacement, velocity, and acceleration in the anteroposterior direction than non-skilled, whereas mediolateral and vertical COM differences were small. In contrast, COP analysis showed that skilled players adopted a more medial COP position and a smaller forward COP shift between backswing and ball impact, indicating that their net COP remained closer to the center of the base of support. No significant group differences were found in COP velocity or acceleration along either axis, although skilled players tended to show lower anteroposterior COP velocity. Together, these findings suggest that skilled players coordinate a more aggressive forward projection of the COM with relatively constrained COP shifts, consistent with an anticipatory and economical postural control strategy during forehand volleys. Anticipatory regulation of COM relative to COP may therefore represent an important contributor to successful volley performance and a potential target for balance- and posture-oriented training interventions in tennis.

Key words. Center of mass, center of pressure, postural control, expertise, forehand volley.

Coordinazione anticipatoria COM-COP come fattore determinante della prestazione di volée di dritto nei tennisti esperti e non esperti

Riassunto. Lo scopo di questo studio era quantificare il modo in cui i tennisti di diversi livelli di abilità regolano il loro centro di massa (COM) e il centro di pressione (COP) durante le volée di dritto e identificare strategie biomeccaniche associate a prestazioni stabili ed efficienti. Sedici giocatori destrimani (8 esperti e 8 non esperti) hanno eseguito volée di dritto standardizzate, registrando la cinematica tridimensionale e le forze di reazione al suolo utilizzando un sistema di motion capture e piattaforme di forza. Le traiettorie di COM e COP (posizione, velocità e accelerazione) sono state estratte lungo gli assi mediolaterale, anteroposteriore e verticale e confrontate tra i gruppi utilizzando t-test per campioni indipendenti. I giocatori esperti hanno mostrato uno spostamento del COM in avanti, una velocità e un'accelerazione in direzione anteroposteriore sostanzialmente maggiori rispetto ai non esperti, mentre le differenze di COM mediolaterale e verticale erano ridotte. Al contrario, l'analisi del COP ha mostrato che i giocatori esperti hanno adottato una posizione del COP più mediale e uno spostamento del COP in avanti minore tra il *backswing* e l'impatto con la palla, indicando che il loro COP netto è rimasto più vicino al centro della base di appoggio. Non sono state riscontrate differenze significative tra i gruppi nella velocità o nell'accelerazione del COP lungo entrambi gli assi, sebbene i giocatori esperti tendessero a mostrare una velocità del COP anteroposteriore inferiore. Insieme, questi risultati suggeriscono che i giocatori esperti coordinano una proiezione in avanti più aggressiva del COM con spostamenti del COP relativamente limitati, in linea con una strategia di controllo posturale anticipatorio ed economico durante le volée di dritto. La regolazione anticipatoria del COM rispetto al COP può quindi rappresentare un importante contributo al successo nelle volée e un potenziale obiettivo per interventi di allenamento orientati all'equilibrio e alla postura nel tennis.

Parole chiave. Centro di massa, centro di pressione, controllo posturale, competenza, volée di dritto.

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Introduction

Tennis volleys represent one of the most technically complex and temporally constrained movements in racket sports. In contrast to baseline strokes, volleys offer minimal preparation time and demand rapid interception of the ball near the net, often requiring immediate redirection of its speed and trajectory under pressure[1,2]. Effective volley execution depends not only on upper-limb kinetics and racket–ball dynamics, but more critically on the regulation of whole-body posture and balance[3]. Successful volley performance requires players to quickly and accurately adjust their body's center of mass (COM), while maintaining control over the center of pressure (COP) beneath their feet[4,5]. The coordination of these two elements allows athletes to stay balanced, move efficiently, and respond to unpredictable ball paths.

Over the past two decades, biomechanical investigations in tennis have predominantly emphasized segmental coordination and joint kinetics. Foundational work has demonstrated that optimal energy transfer from lower extremity extension through trunk rotation to upper-limb acceleration enhances stroke power and consistency[6,7]. Additional research has also investigated ground reaction force (GRF) generation, lower extremity loading, and joint torque generated during different types of strokes[8-10]. Furthermore, upper extremity kinematics and foot position have been highlighted as key factors in stroke consistency and performance[11,12]. However, these investigations often treat postural control as a secondary phenomenon rather than a primary determinant of stroke success, particularly for volleys, where body stability is taxed by split-second timing and spatial constraints.

Research in postural biomechanics has long established that both COM and COP are central to balance control during standing and dynamic tasks[13,14]. In sporting contexts, studies have linked impaired COM–COP coordination to increased injury risk and decreased movement efficiency[15-17]. However, in racket sports - and tennis in particular - studies have systematically quantified whole-body COM and COP kinematics during the forehand volley or compared these profiles between performers of different skill levels[18]. Therefore, a clearer description of how COM and COP trajectories evolve during volley execution may help explain skill-related postural strategies under severe time constraints and provide actionable targets for training and injury-prevention programs.

In summary, while prior research has illuminated many elements of stroke mechanics, a comprehensive, quantitative understanding of COM–COP coordination during tennis volleys – and how this control evolves with skill development – remains a pivotal gap. Addressing this gap will not only clarify the neuromechanical foundations of expert volley performance but also provide actionable targets for balance-oriented training protocols designed to enhance agility, reduce perturbation-induced errors, and mitigate injury risk in competitive play.

This study aims to delineate how tennis players of varying expertise regulate COM and COP during forehand volley execution. Through quantitative analysis of COM-COP coordination patterns, we seek to clarify the biomechanical mechanisms that enable efficient, stable volley performance. The outcomes will deepen our understanding of dynamic balance and motor coordination in tennis, providing an empirical foundation for the development of precision-focused training protocols. We anticipated that skilled and non-skilled would exhibit distinct COM–COP coordination profiles during the tennis volley; specifically, COM positional patterns (displacement in both anteroposterior and mediolateral directions), COM velocity during volley preparation and execution, COM acceleration profiles, COP positional distributions beneath the stance, COP velocity trajectories, and COP acceleration patterns.

Methods

Participants

Sixteen right-handed tennis players (table 1) participated in this study, including 8 non-skilled with 2.6 ± 0.5 years of self-directed training and no professional coaching, and 8 skilled players with 12.7 ± 2.4 years of systematic professional instruction and competitive tournament experience. We note that national ranking was not used as the sole criterion to avoid ambiguity. This study adhered to the principles outlined in the Declaration of Helsinki. The study protocol was explained to all participants, and written informed consent was obtained. The proto-

Table 1. Subject information.

	Age (yrs)	Height (cm)	Weight (kg)	Training period (yrs)
Skilled	24.3 ± 3.3	179.7 ± 5.8	79.3 ± 6.2	12.7 ± 2.4
Non-skilled	23.6 ± 2.8	175.7 ± 6.5	70.6 ± 7.5	2.6 ± 0.5

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col was approved by the Jeonbuk National University Institutional Review Board and conducted in accordance with relevant guidelines and regulations (JBNU2024-09-015-002).

Experimental procedure

Before data collection, the experimental procedures and task requirements were explained to all participants. A standardized warm-up consisting of approximately 10 min of light jogging, dynamic stretching, and practice volleys was performed. To standardize ball delivery and minimize human error, a programmable ball machine (The Tennis, Bucheon, Republic of Korea) was positioned on the opposite side of the net (figure 1) and used to project balls at a constant speed of 20 $m \cdot s^{-1}$ along a consistent trajectory[2,3]. During a brief familiarization phase, the launch angle of the ball machine was individually adjusted such that the ball arrived at approximately chest-to-shoulder height in each player's preferred contact zone[3]. This approach allowed us to present highly repeatable ball-flight conditions and to isolate COM–COP coordination under controlled constraints.

Data acquisition

A total of 57 retroreflective markers (14 mm) were attached to anatomical landmarks to define a full-body, multi-segment model (figure 2), following a previously described marker set[19]. After marker placement, a static calibration trial was recorded with the participant standing in an anatomical position. This trial was used in Visual3D (C-Motion Inc., Germantown, MD, USA) to define a subject-specific biomechanical model for the body, and a racket rigid-body model for event detection (backswing and impact).

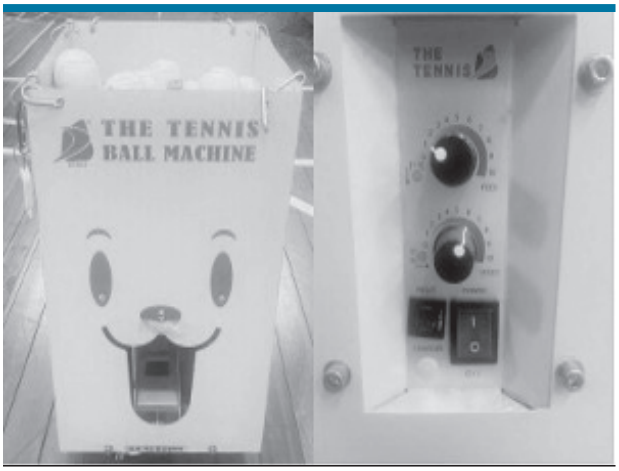

Figure 1. Ball machine.

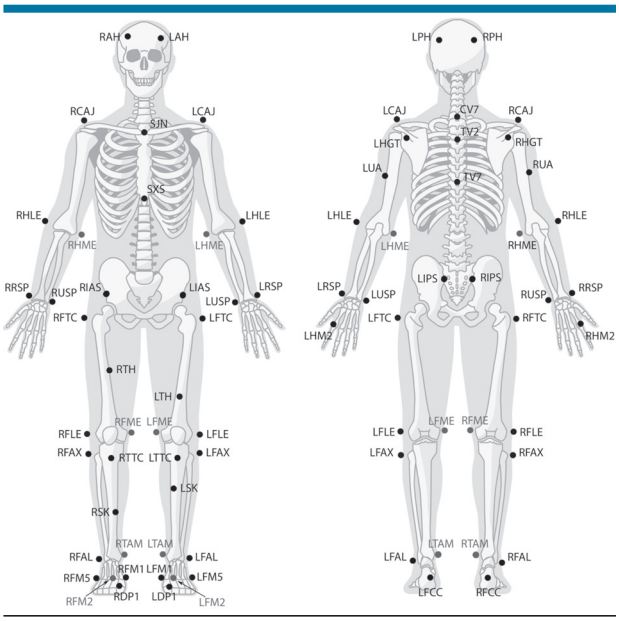

Figure 2. Marker attachment location.

Three-dimensional kinematic data were collected at 240 Hz using a 13-camera infrared motion capture system (OptiTrack, Leyard, USA). Cameras were arranged around the hitting area (figure 3) to ensure full-body and racket-head trajectories were captured during the volley motion.

Ground reaction forces and moments were recorded at 1200 Hz using three force platforms (AMTI, Watertown, MA, USA). The force plates were integrated with the OptiTrack motion-capture system so that kinematic (240 Hz) and analog (1200 Hz) channels were recorded simultaneously in Motive 2.2.0 (OptiTrack, Leyard, USA) under a common trigger and time base.

Phase definition

To focus on the anticipatory and impact-related aspects of COM–COP coordination, each forehand volley was segmented into two key events. The first event was the end of the backswing, defined as the frame at which the racket head reached its highest position or the point farthest away from the ball. The second event was ball impact, identified from the racket-head trajectory as the frame at which the racket head reached its most anterior position along the Y-axis (hitting direction) during the forward swing[20]. Four reflective markers (14 mm) are fixed at the 3, 6, 9, and 12 o'clock positions on the racket to identify key moments (figure 4).

For each successful trial, the analysis interval was defined as the time between the end of the backswing and ball impact. All COM and COP variables were computed within this interval. Because impact was

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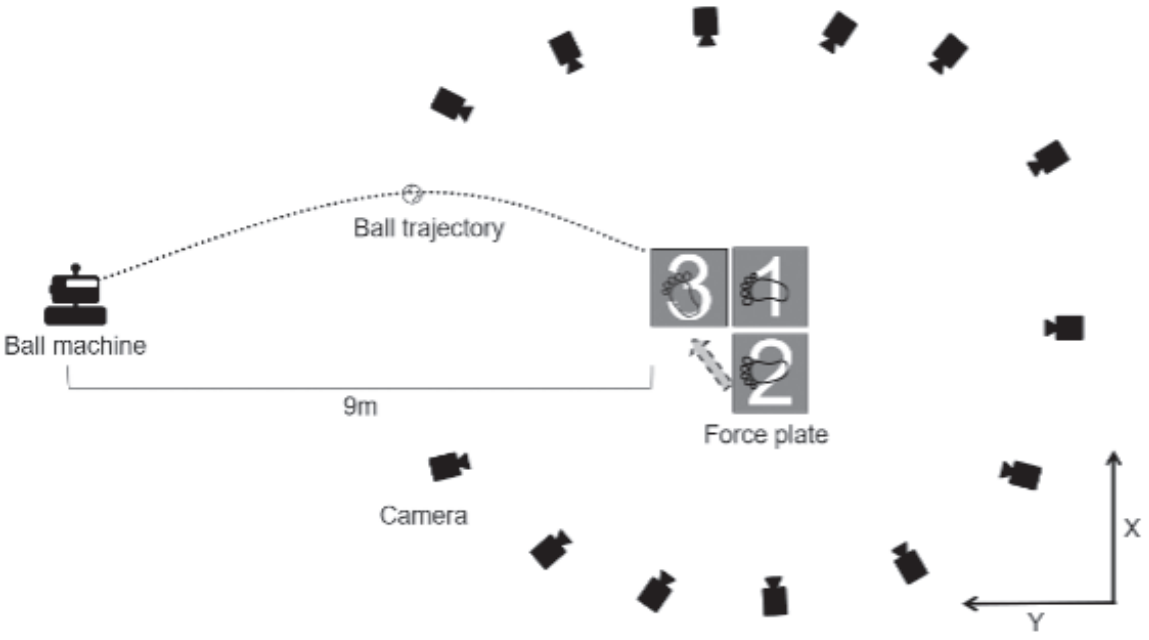

Figure 3. An overhead view of the experimental setup. Participants stood in a ready stance on force plates 1 and 2, executed a standard forehand stroke when the ball arrived, and were required to step onto force plate 3.

identified from racket kinematics sampled at 240 Hz, its timing is discretized to the frame interval (4.17 ms); thus, 'impact' in this study refers to the kinematic event of maximal anterior racket position rather than the exact ball–racket contact instant.

Figure 4. Tennis racket rigid body model.

Data processing, COM, and COP computation

All kinematic and kinetic data were processed in Visual3D. Marker trajectories were low-pass filtered using a fourth-order, zero-lag (bidirectional) Butterworth filter with a cutoff frequency of 6 Hz to remove high-frequency noise while preserving the main movement components[21]. Ground reaction force and moment signals from all force platforms were low-pass filtered with a fourth-order, zero-lag Butterworth filter at 50 Hz before further analysis, in order to preserve the primary kinetic content and attenuate high-frequency artifacts[22].

Whole-body COM trajectories were then obtained automatically in Visual3D from the full-body, multi-segment link model defined in the static calibration trial. Segmental inertial parameters (segment mass and segmental COM location) were assigned within Visual3D according to sex- and stature-specific anthropometric tables[23], based on the classic cadaver data of Dempster[24]. Using these built-in implementations, Visual3D computes the instantaneous whole-body COM position at each time frame as the mass-weighted sum of all segment COM positions expressed in the laboratory coordinate system, following standard multibody mechanics formulations[25]. The laboratory coordinate system was defined with the X-axis oriented mediolaterally (ML), the Y-axis anteroposteriorly (AP; positive anterior), and the Z-axis vertically (positive upward). Whole-body COM was calculated for the participant's body segments only

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(excluding the racket); the racket rigid-body model was used to define backswing and impact events.

Ground reaction forces and moments were processed in Visual3D to obtain the COP under each foot. COP trajectories were calculated automatically by Visual3D's force-plate module from the vertical ground reaction force and the sagittal and frontal plane moments using standard force-plate formulations[25], and subsequently transformed from the force-plate coordinate system to the laboratory frame using the manufacturer-specific calibration matrices embedded in Visual3D.

Because COP was derived from force-plate ground reaction forces and moments while participants held and moved the racket, it reflects the net loading of the participant–racket system. In contrast, whole-body COM was computed from body segments only (excluding the racket), and thus COM–COP comparisons should be interpreted with awareness of this modeling mismatch.

Sample size and sensitivity analysis

Given the exploratory nature of this study and the limited number of eligible players, the total sample size (16 right-handed tennis players; 8 skilled and 8 non-skilled) was determined pragmatically by player availability rather than by an a priori power calculation. After data collection, a post hoc sensitivity analysis was performed using G*Power 3.1 for two-tailed independent-samples t-tests ($\alpha = 0.05$, $1-\beta = 0.80$). This analysis indicated that with 8 players per group, the design was sufficiently powered to detect only large between-group differences; therefore, the present findings should be interpreted as exploratory and hypothesis-generating, and future studies with larger samples are warranted to confirm these results.

Statistical analysis

All statistical analyses were conducted using the individual player as the unit of analysis. For each participant, all technically successful forehand volleys were first identified according to the predefined performance criteria, and trial values for each COM and COP variable within a given phase (backswing and impact) were averaged so that one mean value per player was entered into the group comparison. Data are presented as mean ± standard deviation.

COM and COP position variables in each direction were defined as the net displacement between the last frame of the backswing phase and the impact instant (impact minus backswing). COM and COP velocity and acceleration variables were defined as the mean values over the time interval between these two instants (backswing-to-impact window), computed separately for each axis.

The normality of each variable within each group was checked using the Shapiro–Wilk test; as all variables satisfied the normality assumption, between-group differences (Skilled vs. Non-skilled) were examined using two-tailed independent-samples t-tests for all COM and COP variables. For each comparison, we report the group means, standard deviations, *t* statistic, exact *p* value, and Cohen's d as the standardized effect size. Statistical significance was set at $\alpha = 0.05$.

Results

COM position, velocity, and acceleration

Table 2 summarizes group differences in COM displacement along the X-, Y-, and Z-axes during the tennis volley. No significant group differences were found along the X- or Z-axis. In contrast, skilled players exhibited substantially greater COM displacement along the Y-axis than non-skilled players ($p < .001$, $d = 2.68$).

Table 3 summarizes group differences in COM velocity along the X-, Y-, and Z-axes during the tennis volley. No significant group differences were found along the X- or Z-axis. In contrast, skilled players exhibited markedly greater COM velocity along the Y-axis than non-skilled players ($p < .001$, $d = 3.07$).

Table 4 summarizes group differences in COM acceleration along the X-, Y-, and Z-axes during the tennis volley. No significant group differences were found

Table 2. COM displacement during the tennis volley.

Variables	Group	Mean(m)	SD	*t*(14)	*p*	*d*
COM X	Skilled	0.043	0.023	1.04	0.314	0.52
	Non-skilled	0.031	0.023			
COM Y	Skilled	0.235	0.077	5.36	<.001	2.68
	Non-skilled	0.030	0.076			
COM Z	Skilled	0.018	0.016	0.36	0.722	0.18
	Non-skilled	0.015	0.017			

Values are mean ± SD (m). *t* and *p* are from two-tailed independent-samples t-tests (df = 14). *d* = Cohen's d (Skilled – Non-skilled).

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Table 3. COM velocity during the tennis volley.

Variables	Group	Mean(m·s-1)	SD	*t*(14)	p	d
COM Velocity X	Skilled	0.136	0.049	-0.24	0.814	-0.12
	Non-skilled	0.145	0.096			
COM Velocity Y	Skilled	0.824	0.148	6.15	<.001	3.07
	Non-skilled	0.130	0.283			
COM Velocity Z	Skilled	0.071	0.077	-0.16	0.873	-0.08
	Non-skilled	0.078	0.094			

Values are mean ± SD (**m·s-1**). *t* and *p* are from two-tailed independent-samples t-tests (df = 14). *d* = Cohen's d (Skilled – Non-skilled).

Table 4. COM acceleration during the tennis volley.

Variables	Group	Mean(m·s-2)	SD	*t*(14)	p	d
COM Acceleration X	Skilled	0.532	0.244	-1.05	0.312	-0.53
	Non-skilled	0.748	0.528			
COM Acceleration Y	Skilled	3.214	1.312	4.36	<.001	2.18
	Non-skilled	0.582	1.090			
COM Acceleration Z	Skilled	0.312	0.432	-0.51	0.618	-0.25
	Non-skilled	0.442	0.586			

Values are mean ± SD (**m·s-2**). *t* and *p* are from two-tailed independent-samples t-tests (df = 14). *d* = Cohen's d (Skilled – Non-skilled).

along the X- or Z-axis. In contrast, skilled players exhibited substantially greater COM acceleration along the Y-axis than non-skilled players ($p < .001$, $d = 2.18$).

COP POSITION, VELOCITY, AND ACCELERATION

Table 5 summarizes group differences in COP position along the X- and Y-axes during the tennis volley. Skilled players exhibited a more medial COP position on the X-axis and a smaller forward COP shift (i.e., a COP position closer to the center of the base of support) on the Y-axis compared with non-skilled ($p = 0.009$, $d = -1.51$; $p = 0.031$, $d = -1.19$).

Table 6 summarizes group differences in COP velocity along the X- and Y-axes during the tennis volley. No significant group differences were found in COP

Table 5. COP displacement during the tennis volley.

Variables	Group	Mean(m)	SD	*t*(14)	*p*	*d*
COP X	Skilled	-0.012	0.065	-3.01	0.009	-1.51
	Non-skilled	0.078	0.054			
COP Y	Skilled	0.103	0.086	-2.39	0.031	-1.19
	Non-skilled	0.201	0.078			

Values are mean ± SD (m). *t* and *p* are from two-tailed independent-samples t-tests (df = 14). *d* = Cohen's d (Skilled – Non-skilled).

Table 6. COP velocity during the tennis volley.

Variables	Group	Mean(m·s^{-1})	SD	*t*(14)	*p*	*d*
COP Velocity X	Skilled	0.271	0.309	-0.12	0.904	-0.06
	Non-skilled	0.288	0.242			
COP Velocity Y	Skilled	0.496	0.355	-1.45	0.168	-0.73
	Non-skilled	0.714	0.232			

Values are mean ± SD (**m·s-1**). *t* and *p* are from two-tailed independent-samples t-tests (df = 14). *d* = Cohen's d (Skilled – Non-skilled).

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velocity along either axis ($p \geq 0.168$), although skilled players tended to show lower anteroposterior COP velocity than non-skilled.

Table 7 summarizes group differences in COP acceleration along the X- and Y-axes during the tennis volley. No significant group differences were found along either axis, indicating broadly similar mediolateral and anteroposterior COP acceleration patterns in skilled and non-skilled players.

Discussion

This study compared whole-body COM and COP behavior between skilled and non-skilled tennis players during the forehand volley. Skilled players displayed substantially greater forward COM displacement, velocity, and acceleration in the anteroposterior direction than non-skilled players, whereas mediolateral COM differences were small. At the same time, skilled players exhibited smaller anteroposterior COP displacement and a non-significant tendency toward lower COP velocity in the anteroposterior direction, while COP acceleration measures did not differ between group.

These findings suggest that expert players adopt an anticipatory strategy in which the COM is projected aggressively forward toward the ball to create temporal and spatial pressure, but COP is tightly regulated to maintain stability and allow rapid recovery. This pattern is consistent with modern coordination or coupling frameworks, which view balance as the regulation of the COM state (position–velocity) within a feasible stability region, rather than simply minimizing sway amplitude[14,26,27].

COM dynamics and offensive forehand volley performance

Skilled players exhibited significantly greater forward (anteroposterior) COM displacement, velocity, and acceleration during the forehand volley. This is consistent with previous tennis volley research showing that, under fast incoming ball speeds and severe time constraints, players must initiate movement rapidly and arrive at an advantageous hitting position, with a clear forward execution tendency in the pre-impact phase to complete an effective volley[28]. From a coordination-control perspective, tennis strokes are often summarized by two broad strategies: power-oriented strokes (e.g., serve and groundstrokes) rely more on sequential multi-segment coordination to generate high racquet-head speed, whereas precision-oriented strokes (e.g., net volleys) typically involve fewer contributing segments and a more "unit-like" or compact control pattern[29]. Conceptually, this forward-shifted COM state can also be interpreted using dynamic-balance state-space models, in which balance control depends on the COM position–velocity state relative to feasible stability limits[14,30].

Similar COM-forward strategies have been reported in other explosive or interception tasks. For example, studies in soccer kicking and change-of-direction maneuvers have shown that high-level players allow larger COM excursions in the direction of motion to generate higher approach momentum, while relying on precise timing of ground reaction forces to remain within their stability limits[31,32]. Our data suggest that this whole-body forward drive extends to the forehand volley, where efficient forward COM propulsion toward the ball may be one mechanism supporting effective execution under severe time constraints.

COP behavior, postural efficiency, and expertise

For COP, skilled players exhibited smaller AP (Y) COP displacement and AP COP velocity, along with a more medial COP position (ML/X) compared with non-skilled players. This combination suggests that skilled performers can produce the required forward COM motion while keeping the base-of-support regulation more economical in the AP direction – i.e., less "extra" COP excursion is needed to stabilize the task. Similar expertise-related reductions in postural sway have been reported in tennis populations under static or stance-based balance tests: higher-level tennis players demonstrate lower COP area and mean velocity than lower-level or non-athlete controls, especially under more challenging sensory or stance conditions[25]. Evidence from other racket sports is broadly consistent; for instance, higher-performance badminton players show distinct (often reduced) CoP sway characteristics relative to lower-level players, sup-

Table 7. COP acceleration during the tennis volley.

Variables	Group	Mean(m·s^{-2})	SD	t(14)	p	d
COP Acceleration X	Skilled	1.596	2.063	0.41	0.689	0.20
	Non-skilled	1.251	1.207			
COP Acceleration Y	Skilled	2.460	1.578	-0.56	0.585	-0.21
	Non-skilled	2.765	1.353			

Values are mean ± SD (**m·s-2**). t and p are from two-tailed independent-samples t-tests (df = 14). d = Cohen's d (Skilled – Non-skilled).

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porting the notion that long-term racket-sport training is associated with refined postural regulation[33].

Mechanistically, COP can be viewed as the foot–ground "control signal" that modulates the ground-reaction-force moment to accelerate and regulate COM motion[27,34]. Experts in various sports – gymnastics, judo, soccer, and volleyball – tend to exhibit more regular COP patterns, lower sway amplitudes, and reduced reliance on visual feedback compared with novices[17,35,36]. Our results are compatible with this "postural efficiency" interpretation: non-skilled players appear to rely on larger, faster COP oscillations in the AP direction, likely reflecting delayed or over-corrective control, whereas experts keep COP closer to the center of the base of support, relying more on precisely timed anticipatory actions than on reactive corrections.

Integrated COM and COP patterns and anticipatory postural adjustments

The combination of larger forward COM motion and smaller AP COP excursions suggests that skilled players achieve a more favorable coupling between COM and COP. Rather than simply minimizing sway, experts appear to actively "shape" COP so that the COM state remains within a narrow corridor inside the feasible stability region while moving rapidly toward the ball. This is in line with theoretical and experimental work showing that balance is maintained by regulating the COM state (position–velocity) relative to COP and to the boundaries of stability, rather than keeping COM fixed[14].

From a neuromuscular control perspective, this pattern likely reflects superior anticipatory postural adjustments (APAs). APAs are feedforward activations of postural muscles that precede voluntary movement or external perturbations, shifting COP and COM into a mechanically advantageous state[37,38]. In racket sports, APAs have been shown to differentiate experts from novices: for example, expert table tennis players display earlier and larger APA activity in trunk and lower-limb muscles under high temporal pressure, enabling them to maintain stability while executing very fast arm movements[39]. Our COM–COP findings are consistent with the idea that skilled tennis players use more effective APAs before and during the forehand volley. By pre-shifting COM forward and constraining COP within a smaller AP range, experts can "pre-place" the body in a mechanically advantageous configuration, reducing the need for large reactive corrections when contacting the ball. This interpretation is compatible with EMG studies of tennis volleys and forehand strokes, which have reported increased pre-impact activation and co-contraction of upper-limb and trunk muscles, particularly as ball speed and impact demands increase[40,41].

Practical implications

From a practical standpoint, the present findings highlight that coaching for the forehand volley should not focus solely on racket and upper-limb technique. Instead, training should also target whole-body COM propulsion and postural efficiency. Exercises that encourage players to project COM forward toward the net – such as controlled step-in volleys, split-step plus immediate forward lunge drills, and constraint-led games that reward net penetration – may help non-skilled players adopt a more expert-like COM strategy[42]. At the same time, balance and postural training should be designed to improve COP control under tennis-specific temporal constraints rather than just reducing sway in quiet stance. Dynamic balance tasks that incorporate racket swings, unpredictable ball trajectories, or dual-task (cognitive) demands have been shown to enhance anticipatory control and perceptual–cognitive skills in racket sports.

Incorporating such tasks into volley training may help players learn to keep COP tightly regulated while moving COM aggressively, thereby improving both stability and offensive potential at the net.

Limitations

Several limitations should be acknowledged. First, this exploratory study used a small sample; therefore, between-group estimates – despite large effect sizes - should be interpreted cautiously and replicated in larger cohorts. Second, COP was derived from force plates in a controlled laboratory setting and may not fully represent postural control in match play. Third, whole-body COM was computed from a human multi-segment model without the racket, whereas COP reflects the net force-plate loading while holding/moving the racket; thus COM and COP comparisons may be subject to a small system-mismatch bias and unmodeled influences of racket geometry/inertia (and inter-individual equipment differences)[43]. Finally, our findings are specific to a controlled forehand-volley task and should not be generalized to all volley conditions; nevertheless, the consistent COM and COP differences between skilled and non-skilled players suggest that anticipatory regulation of COM and COP behavior may contribute to forehand-volley performance.

Conclusion

This exploratory study indicates that skilled tennis players demonstrate more anticipatory and econom-

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ical COM and COP strategies during forehand volleys compared with non-skilled players. Skilled athletes shifted their COM forward with greater velocity and acceleration and maintained tighter, more centralized COP trajectories, while non-skilled relied more on reactive balance strategies.

Conflicts of interest. The authors declare that there is no conflict of interest.

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Corresponding authors:
Zhengxiao Zhang
E-mail: zhangzhengxiao0706@jbnu.ac.kr
Sukwon Kim
E-mail: rockwall@jbnu.ac.kr