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Lower Extremity Coordination Variability and Motor Control During Tennis Lateral Recovery: The Role of Forehand Stance

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Abstract

Purpose: The primary objective of this research is to examine variations in lower extremity segmental coupling coordination variability (CV) during the recovery phase following a tennis stroke, specifically comparing open, semi-open, and neutral stances.

Methods: This study evaluated fourteen advanced male players performing forehand strokes and lateral recoveries across these stances. Kinematic data from a motion capture system and a modified vector coding technique were used to calculate segmental CV of eight lower extremity coupling pairs during brake and push-off phases.

Results: A one-way repeated measures analysis of variance (ANOVA) and one-dimensional statistical parametric mapping (SPM1d) analysis revealed that stances significantly alter coordination strategies. During the push-off phase, the open stance exhibited significantly higher CV in pelvis sagittal versus thigh sagittal coupling compared to the semi-open stance ($P < 0.05$, $d = 0.78$). Furthermore, during the 57.5%-61.3% period of this phase, thigh sagittal versus shank frontal coupling CV was significantly lower in the open stance.

Conclusion: These findings indicate that open stance recovery utilizes unique coordination strategies, characterized by increased pelvis-thigh and decreased thigh-shank CV. From a motor control perspective, reduced distal variability likely stabilizes the knee for optimal lateral force transmission. Conversely, the increased proximal variability likely serves as a compensatory mechanism to facilitate rapid trunk repositioning and maintain dynamic balance. Ultimately, this task-specific trade-off between distal stability and proximal flexibility highlights the movement efficiency of advanced tennis players.

Keywords: tennis, coordination variability, recovery movement, forehand stance, vector coding technique

1 Introduction

Tennis is a globally popular sport with participation from over 200 countries [30]. However, as a high-intensity intermittent sport involving multidirectional displacements [29], tennis is frequently accompanied by a substantial number of sports injuries. Studies have reported an incidence of 3.49 injury cases per 1000 hours of tennis training, with the most common being joint injuries (29.5%), followed by tendinopathy (22.1%), which are predominantly located in the ankle (20%) and wrist (15.8%) [28]. Other studies have indicated that among injuries occurring in tennis, the probability of lower extremity injuries is higher than that of the upper extremities. The incidence of musculoskeletal injuries in the lower extremities ranges from 31% to 67%, compared to 20% to 49% for the upper extremities, and 3% to 21% for the trunk [1]. During a tennis match, to efficiently transition to the next stroke, players typically need to perform a significant number of recovery movements between consecutive strokes. These recovery movements primarily consist of lateral cross-over steps and lateral translation, movement patterns that are often associated with lower extremity injuries [27], such as anterior cruciate ligament injuries [10], and ankle injuries [36]. Given the limited attention directed towards the recovery movement post-stroke, conducting relevant biomechanical research on tennis recovery movements is highly necessary to reveal the characteristics of tennis-related lower extremity musculoskeletal injuries, thereby providing new insights for further injury risk management. This aligns with the broader biomechanical consensus that understanding lower limb movement strategies is essential for injury prevention [39].

This phenomenon is related to the specific movement characteristics of tennis. Unlike cyclical sports such as running and cycling, tennis players execute numerous lateral movements, start-stop actions, changes of direction, and rotational striking motions during training and competition. These actions often impose immense stress on the lower extremity musculoskeletal system [22]. Previous tennis-related research has typically focused on scoring-oriented actions, such as groundstrokes and serves [18], [20]. For instance, previous studies investigating the biomechanical differences of forehand strokes in open, semi-open, and neutral stances found that adjusting the relative direction of the front foot when athletes use a neutral stance for baseline backhand strokes might improve athletic performance and reduce the risk of ankle injury [16]. Similar to findings in other sports where technique modifications significantly influence patellofemoral joint loading and knee pain [6]. Compared to the neutral stance, executing a forehand stroke in an open stance appears more likely to induce specific knee injuries, such as patellar tendinitis, knee osteoarthritis, and meniscus tears [25], and the open stance also subjects the hip to greater loads, leading to potential hip injuries [26].

Movement coordination was defined by Bernstein as the mastery of redundant degrees of freedom within a system [4], and coordination variability (CV) is an indicator used to quantify the degree of fluctuation in coordination patterns [7]. From a dynamical systems perspective, movement variability plays a functional role in motor control rather than representing mere system noise [3]. According to the variability-overuse hypothesis, healthy motor function relies on maintaining CV within an optimal functional window [14]. Reduced CV reflects a constrained motor pattern that concentrates repetitive stress on localized tissues, potentially leading to overuse injuries, whereas excessive CV indicates joint instability [15]. CV translates the coordination strategies adopted throughout the entire movement phase into a single numerical value, rather than merely comparing the synchronous motion of two joints during the action. Joint coordination during movement can be calculated using a modified vector coding technique [7]. An excessively low CV reflects a constrained motor pattern; while this freezing of degrees of freedom may be necessary to secure joint stability during explosive task[4], it theoretically concentrates repetitive stress on localized structures[14], [15]. Conversely, a higher CV provides necessary flexibility; while excessive variability may indicate instability, an optimal increase in proximal CV could serve as a compensatory mechanism to facilitate rapid trunk repositioning when the lower extremity is biomechanically constrained[16], [37].

This study aims to investigate the differences in lower extremity segmental coupling variability during the recovery movement after a tennis stroke across different stances (open, semi-open, and neutral stances). Given adequate hip range of motion is required for the transfer of energy along the kinetic chain during open stance strokes [37], we hypothesized that the lateral recovery phase from this stance would alter the CV. Specifically, we hypothesized that compared to neutral and semi-open stances, the open stance would exhibit decreased CV in distal lower-limb couplings, accompanied by increased CV in proximal couplings.

2 Methods

2.1 Participants

Fourteen advanced male tennis players participated in this study. The participants' basic characteristics were as follows: age 22.33 ± 1.63 years; height 174.83 ± 8.72 cm; body mass 67.17 ± 3.76 kg; body mass index 22.03 ± 1.53 kg/m^2; years of training experience 11.14 ± 1.10 years; International Tennis Number (ITN) 3 or 4; all were right-handed. According to the International Tennis Federation (2009) criteria, ‘ITN 4 players demonstrate proficient use of power and spin, begin to cope with incoming ball pace, exhibit stable footwork, possess the ability to control stroke depth, and start adapting match strategies based on their opponents’.

‘ITN 3 players possess excellent shot anticipation capabilities, and typically exhibit outstanding stroke mechanics or attributes around which their game systems can be structured’ [23]. Prior to the experiment, participants were fully informed of the experimental procedures. The inclusion criteria were as follows: (1) no lower extremity surgery or injury within the past six months; (2) training frequency: a minimum of 5 days/week, tennis-specific training volume: a minimum of 12 hours/week; (3) active participation in national- or provincial-level competitions (defined as competing in 15 to 25 officially sanctioned tournaments per year).The novices or lower-level athletes exhibit unstable kinetic mechanisms and intra-individual movement variability. Therefore, a highly homogeneous cohort of advanced players was required to isolate the mechanical effects of the different stances. This research protocol was approved by the Ethics Committee of Ningbo University (TY2025082).

2.2 Experimental Procedure

During the experiment, as shown in Figure 1(A), 46 reflective markers were placed on specific anatomical landmarks of the participants [12], [35]. A Vicon motion capture system equipped with ten infrared cameras (Oxford Metrics Ltd., Oxford, UK, 200 Hz) was used to collect kinematic data [13], [17], [21], [34], [40], and two three-dimensional force plates (Kistler Group, Winterthur, Switzerland, 2000 Hz) were utilized to acquire kinetic data [5].

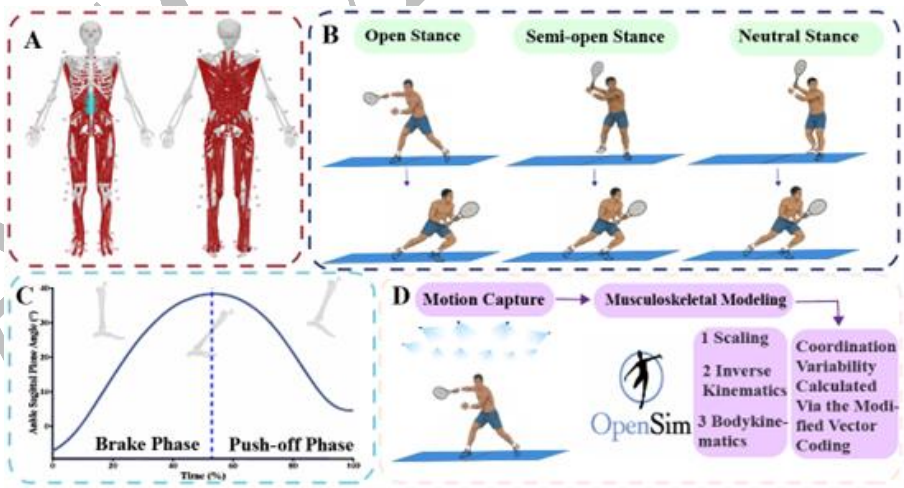

Figure 1. Data acquisition process and processing: (A) Reflective marker placement locations; (B) Schematic of recovery movements following three different hitting stances; (C) Movement phases divided based on the peak ankle sagittal plane angle; (D) Motion capture, OpenSim inverse kinematics calculation, and coordination variability calculation.

Prior to motion capture, participants observed the experimental procedures and the recovery movements following three types of forehand strokes (open, semi-open, and neutral stance) demonstrated by a professional coach. For the neutral stance, the participants' feet and knees were perpendicular to the net, whereas for the open stance, they were parallel to the net. The semi-open stance refers to any foot position between the neutral stance and the open stance [25]. They were given ample time to familiarize themselves with the experimental environment [31], and the designated markers, and practiced all forehand stroke recovery movements [25]. The testing sequence of the three movements was completely randomized to prevent order effects. The athletes performed a five-minute treadmill warm-up to prevent injuries, followed by 5 to 7 minutes of practicing the respective test movements. They were required to perform each test trial with maximal effort. Five successful trials were recorded for the recovery movement of each stance. A successful trial was defined as correctly executing the forehand stroke and rapidly transitioning into the recovery movement immediately thereafter.

As shown in Figure 1(B), for the recovery movement following an open stance stroke, the athlete's feet were parallel to the net, standing behind the two force plates. When the movement initiated, the athlete first stepped the left foot onto force plate 2, followed by the right foot onto force plate 1 to execute the striking motion, and subsequently performed the recovery movement to the left side. For the recovery movement following a semi-open stroke, the feet are positioned at a 90° angle to the net. The athlete is positioned at a 45° angle to the rear left of the force plates. First, the left foot steps onto force plate 2, followed by the right foot landing one step behind force plate 2. At this point, both feet are oriented at a 45° angle to the net. After completing the swing, the right foot follows through to force plate 1, executing the recovery movement laterally to the left. For the recovery movement pattern following a neutral stance stroke, which is similar to the semi-open stance, during the preparation phase, the athlete is positioned at a 45° angle to the rear left of the force plates, with the feet oriented at a 90° angle to the net. The two feet step onto force plate 2 and a distance one step behind force plate 2, respectively. After completing the stroke, the right foot follows through to force plate 1, and the athlete then executes the recovery movement laterally to the left. All movements involved hitting an imaginary ball while holding a racket [16].

2.3 Data Processing

Raw kinematic and kinetic data were pre-processed using Vicon Nexus (Version 2.12, Oxford Metrics Ltd., Oxford, UK). A zero-lag fourth-order Butterworth low-pass filter was applied, with a cutoff frequency of 6 Hz for motion capture data [2], [33]and 50 Hz for force data. A force plate foot contact event was defined when the ground reaction force (GRF) exceeded a 20 N threshold [35].

Subsequently, the OpenSim (Version 4.5, Stanford University, Stanford, USA) environment was utilized for model scaling and inverse kinematic calculations on the experimental data to determine joint angles. The segment angles of the pelvis, thigh, shank, and rearfoot were represented as the orientation of the segment reference frame (fixed to the segment) relative to the global reference frame [7]; the segment reference frame was aligned with the global reference frame in a neutral position, as previously defined [9]. The segment angle data were normalized to a standard standing posture [7].

This study adopted a modified vector coding technique. The eight segment coupling pairs of interest were selected: (1) pelvis frontal vs. thigh frontal, (2) pelvis sagittal vs. thigh sagittal, (3) thigh frontal vs. shank frontal, (4) thigh sagittal vs. shank sagittal, (5) thigh sagittal vs. shank frontal, (6) shank sagittal vs. rearfoot sagittal, (7) shank transverse vs. rearfoot frontal, and (8) shank frontal vs. rearfoot frontal. These specific segment couplings were selected as they are primarily associated with lower extremity joint loading and motor control mechanisms in tennis. First, the segment angle data of interest for the three recovery movements were time-normalized. Segmental coordination was derived from the angle-angle plots of the segments of interest, where the proximal joint served as the abscissa and the distal joint as the ordinate [7]. The coupling angle (γ_i) was defined as the angle formed by the vector connecting two consecutive time points relative to the right horizontal axis (Eq.1) [7].

$$\gamma_i = tan^{-1}\left(\frac{\left(\theta_{(D(i+1))} - \theta_{(Di)}\right)}{\left(\theta_{(P(i+1))} - \theta_{(Pi)}\right)}\right) \cdot \frac{180}{\pi} \qquad (Eq.1)$$

$$\bar{x_i} = \frac{1}{n}\sum_{i=1}^{n} cos\,\gamma_i \qquad (Eq.2)$$

$$\bar{y_i} = \frac{1}{n}\sum_{i=1}^{n} sin\,\gamma_i \qquad (Eq.3)$$

$$\overline{\gamma_i} = tan^{-1}\left(\frac{\overline{y_i}}{\overline{x_i}}\right) \cdot \frac{180}{\pi} \quad (Eq. 4)$$

$$CV_i = \sqrt{2\left(1 - \sqrt{\overline{x_i}^2 + \overline{y_i}^2}\right)} \cdot \frac{180}{\pi} \quad (Eq. 5)$$

Where i is the i-th time point after data normalization, and θ_D and θ_P represent the angles of the distal and proximal segments, respectively [7].

Using circular statistics, the coordination variability (CV_i) was calculated as the circular standard deviation of the i-th coupling angle across the five trials for each set of normalized data (Eqs 2-5), where n represents the n-th data point among the five sets, and $\overline{x_i}$ and $\overline{y_i}$ denote the horizontal and vertical components of the mean coupling angle at the i-th point [7]. As depicted in Figure 1(C), the recovery movement phase was divided into a brake phase and a push-off phase based on the peak flexion/extension angle of the ankle joint in the sagittal plane.

2.4 Statistical Analysis

Statistical analyses were divided into mean data analysis and one-dimensional statistical parametric mapping (SPM1d) analysis. For the mean data analysis, statistical procedures were performed using SPSS software (Version 19, IBM Corporation, New York, USA). A one-way repeated measures analysis of variance (ANOVA) was utilized to analyze the differences in phase CV for the seven pairs across the three post-forehand recovery movements. First, data normality was assessed using the Shapiro-Wilk test, and the sphericity assumption was evaluated using Mauchly's test. If the sphericity assumption was violated, the degrees of freedom were corrected using the Greenhouse-Geisser method. When the main effect of ANOVA was significant, a post-hoc paired t-test was conducted. For pairwise post-hoc comparisons, the Bonferroni correction was applied to adjust the significance level to control for Type I errors associated with multiple comparisons. The effect size was interpreted using partial eta squared (η_p^2): large effect > 0.14, medium effect > 0.06, small effect > 0.01 [8], with the α level set at 0.05. For post-hoc pairwise comparisons, Cohen's d and Cohen's d_z were used to evaluate the magnitude of effect sizes, which were classified as: large effect > 0.8, medium effect > 0.5, small effect > 0.2 [8].

Segmental CV time series were compared across the three stances using statistical parametric mapping, one-way repeated measures ANOVA ($\alpha = 0.05$) implemented through the open-source spm1d package (version 0.4, www.spm1d.org) in Python (version 3.11.14). For each significant post-hoc result, a window-based standardized effect size (Cohen's d_z) was calculated to quantify the magnitude and direction of the differences between conditions.

3 Results

3.1 Discrete Mean Coordination Variability

The CV values across all evaluated stances demonstrated relatively narrow standard deviations, reflecting highly stable lower-extremity kinetic execution during the trials. As shown in Figure 2(B), during the brake phase, a significant main effect was observed for pelvis sagittal vs. thigh sagittal ($F = 3.72$, $P = 0.038$, $\eta_p^2 = 0.22$), but the post-hoc paired t-test revealed no significant difference. As illustrated in Figure 3(B), during the push-off phase, a significant main effect existed for pelvis sagittal vs. thigh sagittal ($F = 4.24$, $P = 0.025$, $\eta_p^2 = 0.25$), and the post-hoc paired t-test identified a significant difference between the semi-open stance and open stance ($P = 0.035$, $d = 0.78$). A significant main effect was also found for shank frontal vs. rearfoot frontal ($F = 3.85$, $P = 0.034$, $\eta_p^2 = 0.23$), yet the post-hoc paired t-test indicated no significant difference.

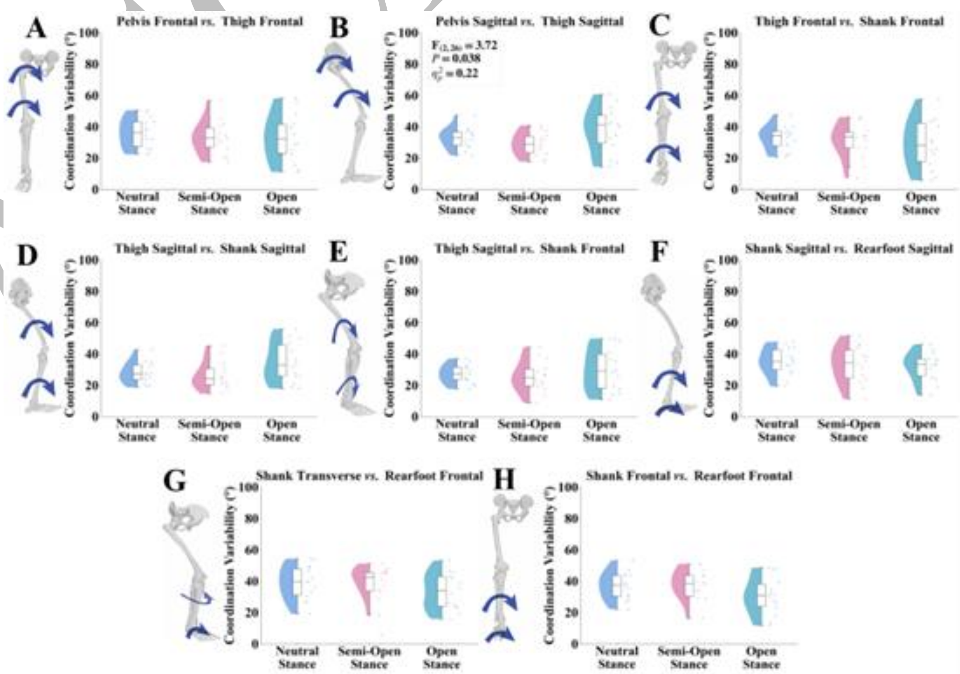

Figure 2. Coordination variability data of the segments of interest during the brake phase of the post-stroke recovery movement across the three stances.

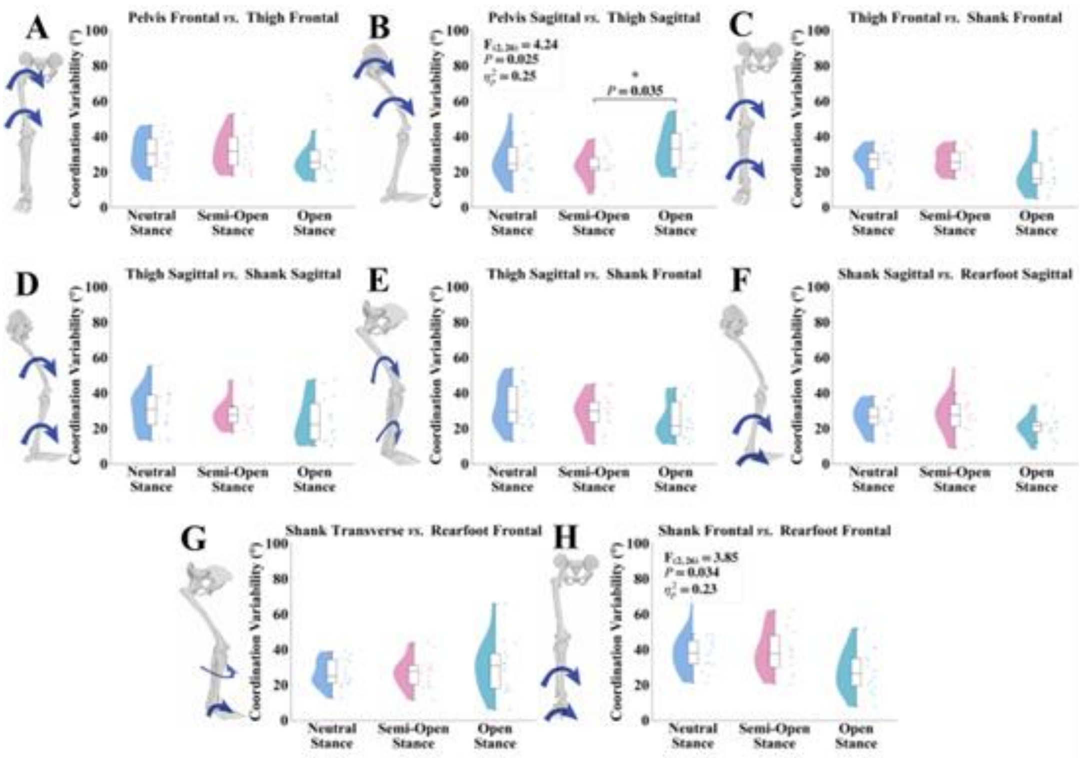

Figure 3. Coordination variability data of the segments of interest during the push-off phase of the post-stroke recovery movement across the three stances.

3.2 SPM1d Results for Coordination Variability

Regarding the SPM1d time series results for CV, as depicted in Figure 4(A), during the brake phase, a significant main effect was present for thigh sagittal vs. shank frontal (46.6-56.5%, F ≥ 7.78, P = 0.001, η_p^2 = 0.42), but the post-hoc paired t-test showed no significant difference. As shown in Figure 4(B), shank sagittal vs. rearfoot sagittal exhibited a significant main effect (95.7%-99.0%, F ≥ 8.08, P = 0.028, η_p^2 = 0.45), though the post-hoc paired t-test revealed no significant difference. As shown in Figure 5(A), in the push-off phase, a significant main effect was found for pelvis sagittal vs. thigh sagittal (93.0%-93.0%, F ≥ 8.66, P = 0.05, η_p^2 = 0.4), but the post-hoc paired t-test indicated no significant difference. As depicted in Figure 5(B), in the push-off phase, thigh sagittal vs. shank frontal demonstrated a significant main effect (55.9%-62.1%, F ≥ 7.68, P = 0.014, η_p^2 = 0.51), the post-hoc paired t-test revealed a significant difference between the semi-open and open stances (57.5%-61.3%, P = 0.008, d_z = 1.404). As shown in Figure 5(C), shank sagittal vs. rearfoot sagittal exhibited a significant main effect (0.0%-2.3%, F ≥ 7.87, P = 0.04, η_p^2 = 0.44), yet the post-hoc paired t-test showed no significant difference.

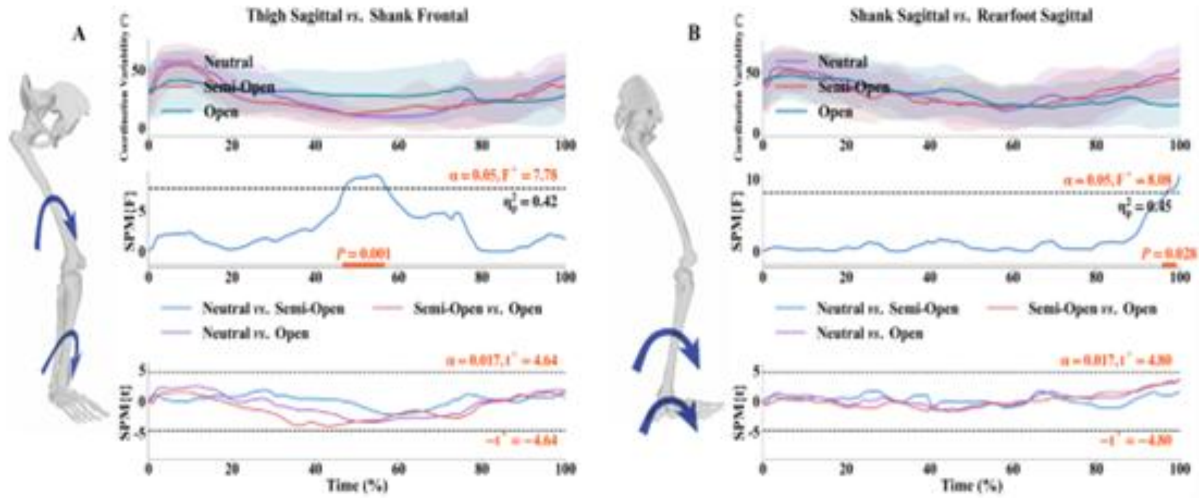

Figure 4. Coordination variability time series results during the brake phase of the recovery movement across different stances. (A) thigh sagittal *vs*. shank frontal; (B) shank sagittal *vs*. rearfoot sagittal. Coordination variability (°): mean ± standard deviation; SPM{F}: main effect results of SPM1d for coordination variability, with the solid blue line representing the statistical parametric mapping {F} statistic and the dashed black line indicating the significance threshold; SPM{t}: post-hoc t-test results, with the solid blue, purple, and red lines representing the statistical parametric mapping {t} statistic, and the dashed black lines indicating the significance thresholds and directions. SPM: statistical parametric mapping.

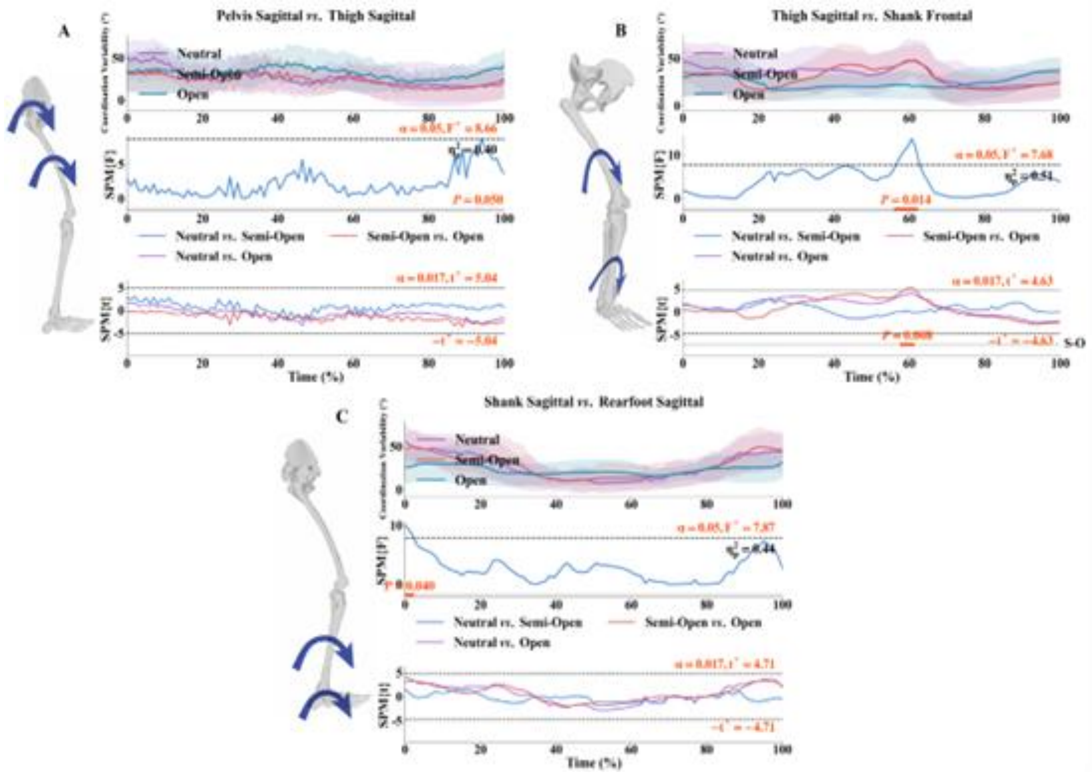

Figure 5. Coordination variability time series results during the push-off phase of the recovery movement across different stances. (A) pelvis sagittal vs. thigh sagittal; (B) thigh sagittal vs. shank frontal; (C) shank sagittal vs. rearfoot sagittal. Coordination variability (°): mean ± standard deviation; SPM{F}: main effect results

of SPM1d for coordination variability, with the solid blue line representing the statistical parametric mapping {F} statistic and the dashed black line indicating the significance threshold; SPM{t}: post-hoc t-test results, with the solid blue, purple, and red lines representing the statistical parametric mapping {t} statistic, and the dashed black lines indicating the significance thresholds and directions. S-O: semi-open vs. open. SPM: statistical parametric mapping.

4 Discussion

The primary focus of this study was to utilize segmental CV data to quantify the differences in recovery movements following tennis strokes across various stances, thereby revealing their movement strategies. Our results indicated a concurrent increase in proximal (pelvis-thigh) CV and a decrease in distal (thigh-shank) CV during the open stance push-off phase, which supports our hypothesis. From a dynamical systems perspective, this divergent pattern reflects a task-specific adaptation rather than a uniform systemic change [32]. The decreased thigh-shank CV indicates a constrained motor pattern. Effective energy transfer along the kinetic chain during open stance strokes relies on sufficient hip range of motion [37]. Conversely, the increased pelvis-thigh CV serves as a proximal compensatory mechanism. Because the open stance mechanically restricts natural pelvic rotation compared to the neutral stance, the sensorimotor system must employ greater variability in proximal couplings to facilitate trunk repositioning and maintain balance [16]. Therefore, the simultaneous presence of decreased distal CV and increased proximal CV represents a functional trade-off between distal stability and proximal compensation.

In tennis, the forehand stroke involves a bottom-up sequence of movements termed the ‘kinetic chain’, in which the hip joint is responsible for transferring maximum energy from the lower extremities to the trunk [24]. During the forehand stroke, the hip joint must withstand substantial forces during the flexion, extension, and rotational movements executed by the player to generate a powerful shot [11]. In our study, within the push-off phase, the pelvis sagittal vs. thigh sagittal coupling exhibited significantly higher values for the open stance compared to the semi-open stance. This implies that the open stance entails a greater range of flexion-extension motion in the sagittal plane for the pelvis and thigh segments compared to the semi-open stance. Our results appear consistent with previous research findings regarding the striking phase [24], the open stance involves greater flexion and extension activities. This qualitative observation seems reasonable, as when executing a stroke in an open stance, players are required to generate greater angular momentum around the longitudinal axis and perform a larger range of hip motion compared to the neutral and semi-open stances [25]. Previous research has demonstrated that the open stance forehand elicits significantly greater compressive forces at the hip joint compared to the neutral stance [24]. Consequently, the elevated proximal variability observed here may reflect a coordination strategy to accommodate these heightened kinetic demands. Furthermore, repetitive exposure to high hip joint loads during dynamic rotations may increase the risk of developing hip-related pathologies over time [38]. The current study lacks direct kinetic measurements, such as joint moments or contact forces. Future investigations combining coordination variability with inverse dynamics are required to validate this proposed link.

Our findings demonstrated that during the push-off phase, the CV of the thigh sagittal vs. shank frontal coupling was significantly lower in the open stance compared to the neutral stance. In the open stance, due to the absence of weight transfer in the direction of the stroke, the trunk undergoes greater rotation toward the target [19]. The lack of weight transfer during the push-off phase reduces CV, which may subject the knee joint to repetitive loading [15]. Previous studies have indicated that individuals with less variability in their lower extremity neuromuscular control patterns may experience overuse injuries. For example, fatigue wear of articular cartilage results from the accumulation of micro-damage under repetitive stress [15]. Regarding the decreased thigh-shank CV, we acknowledge that the interpretation of movement variability in the literature is highly nuanced. Reduced CV is not exclusively indicative of a pathological state; rather, it often reflects a functional stabilization strategy [3], [7]. During the high-demand push-off phase, lowering distal variability is likely a necessary mechanical adaptation to secure the knee joint and ensure efficient lateral force transmission. However, while this highly repeatable coordination pattern is functionally beneficial for immediate movement execution, it inherently restricts the distribution of mechanical loads across different articular surfaces [15]. Therefore, it is plausible that the potential knee injury risk may stem from the prolonged, repetitive application of this constrained pattern over the course of a match. This repetition could theoretically concentrate stress on localized structures, rather than low CV being inherently injurious on its own. Furthermore, the SPM1d analysis provides crucial temporal context by identifying a specific significant window (57.5%–61.3%) during the push-off phase where this distal CV reduction occurs. Biomechanically, the mid-to-late portion of the push-off phase aligns with the generation of peak propulsive ground reaction forces [5], which are required to accelerate the center of mass laterally. This temporally specific reduction suggests that the motor system adopts a conservative coordination strategy to stiffen the distal joints, ensuring mechanical stability for force transmission [7]. The open stance features relatively extensive hip joint motion and lower knee coupling CV. We hypothesize that athletes reduce distal joint CV to accomplish an efficient push-off, thereby more effectively transitioning to the next stroke. Compared to other stances, this reflects the unique hip-knee synergistic strategy exhibited by the open stance for efficient recovery. When confronted with the demands of rapid force generation and specific postural constraints, this alteration in coordination patterns reflects a compensatory interaction within the lower extremity kinetic chain aimed at ensuring movement execution efficiency [3].

We found that significant differences across stances primarily occurred in the sagittal plane. Compared to other stances, this may represent a unique coordination strategy employed by elite athletes during open stance recoveries. On the other hand, because both the neutral stance and the semi-open stance involve a follow-through action, specifically, the right foot stepping forward onto the force plate after the stroke before returning laterally, the recovery movement patterns of these two stances are highly similar. Consequently, no significant differences in CV were found during the recovery phase between these two stances.

Several limitations of this study should be acknowledged, which also provide directions for future research. First, the sample size of the current study is relatively small, this strict sampling prevented confounding from the unstable kinetic mechanisms typical of lower-level players, limiting generalizability to females or novices. Second, utilizing an imaginary ball compromised ecological validity by removing the perceptual constraints inherent in real match play. However, since unanticipated stimuli significantly alter lower extremity coordination strategies [36], using an actual approaching ball would compel athletes to make spontaneous perceptual-motor adjustments. This resultant kinematic noise could easily confound the baseline coordination differences inherently caused by the stances. Thus, while this highly controlled paradigm restricted natural perceptual-motor exploration, it was a necessary methodological trade-off. Consequently, the observed coordination variability may not fully reflect the dynamic adaptations and movement strategies of unconstrained competition. Finally, future studies integrating kinetic analysis would facilitate a more comprehensive understanding of the neuromuscular driving mechanisms underlying these movement patterns.

From a practical training perspective, understanding these stance-specific coordination strategies provides valuable insights into movement efficiency. Coaches might consider these kinematic differences when designing load-management protocols, potentially favoring the neutral stance during certain training phases to proactively modulate synergistic loading along the lower-extremity kinetic chain.

5 Conclusion

This study characterizes distinct lower extremity coordination patterns during the lateral recovery phase of different tennis forehand stances. Specifically, the open stance elicits a divergent coordination strategy during the push-off phase, characterized by increased proximal (pelvis-thigh) CV alongside decreased distal (thigh-shank) CV. From a motor control and sports performance perspective, these kinematic alterations reflect functional adaptations to specific task constraints. The reduced distal variability likely acts to stabilize the knee for optimal lateral force transmission, whereas the increased proximal variability serves as a compensatory mechanism to facilitate rapid trunk repositioning and maintain dynamic balance. Ultimately, this task-specific trade-off between distal stability and proximal flexibility highlights the movement efficiency of advanced tennis players during rapid court recovery. Therefore, future studies incorporating inverse dynamics are necessary to objectively evaluate actual joint loading.

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