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RESEARCH ARTICLE

Video-based phase analysis of technical errors in fundamental tennis skills among physical education students

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ABSTRACT

Background: Technical errors frequently occur during the acquisition of fundamental tennis skills, yet limited studies have systematically examined these errors across different movement phases using video-based analysis among physical education students. **Objectives:** This study aimed to analyze technical errors across four fundamental tennis techniques and three movement phases using a video-based analysis approach. **Methods:** A cross-sectional observational study was conducted with 36 physical education students selected through purposive sampling. Participants performed forehand, backhand, volley, and serve techniques, which were analyzed using video recordings and Kinovea software. Technical errors were evaluated independently by two trained observers across the preparation, execution, and follow-through phases. Data were analyzed using descriptive statistics and inferential analysis. **Results:** The serve demonstrated the highest proportion of technical errors (31.1%), followed by the forehand (28.3%), backhand (26.4%), and volley (14.2%). Errors occurred most frequently during the execution phase (45.0%). Statistical analysis indicated significant differences in technical error scores among the four techniques (p < .001). **Conclusion:** Video-based phase analysis enabled detailed identification of technique- and phase-specific technical errors in beginner tennis performers. These findings provide evidence to support phase-specific feedback strategies and instructional planning for improving fundamental tennis skills in physical.

Keywords: Tennis; technical errors; video-based analysis; movement phase; physical education

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INTRODUCTION

Tennis is a complex sport that requires high levels of technical precision, coordination, and movement control to execute fundamental skills such as the forehand, backhand, serve, and volley effectively. Successful performance in tennis depends on the integration of biomechanical principles involving kinematics, kinetics, muscle coordination, and sequential body movements during the preparation, acceleration, and follow-through phases (Brito et al., 2024; Brocherie & Dinu, 2022). Previous studies have demonstrated that even minor disruptions in inter-segmental coordination may substantially influence stroke accuracy, movement efficiency, and overall performance quality (Bobrownicki et al., 2019; Jacquier-Bret & Gorce, 2024). Therefore, mastering fundamental tennis techniques is essential not only for performance improvement but also for reducing injury risk and promoting long-term skill development among tennis players (Forte et al., 2021).

Despite the importance of technical mastery, technical errors remain a major challenge in tennis instruction, particularly among beginner performers and physical education students. Common errors involving timing, body positioning, movement coordination, and racket control frequently reduce stroke effectiveness and may increase the risk of musculoskeletal injury (Brocherie & Dinu, 2022; Kibler et al., 2022). In competitive contexts, technical inefficiency has also been associated with increased unforced errors and reduced match performance outcomes (Peiris et al., 2025). From a motor learning perspective, repetitive practice without effective corrective feedback may unintentionally reinforce inefficient movement patterns, making technical errors more difficult to modify over time (Bobrownicki et al., 2019; Marriott & Birmingham, 2023; Ye & Liu, 2025). This indicates that early identification of technical deficiencies is important for improving movement quality and optimising skill acquisition processes.

In recent years, video-based motion analysis has become increasingly important in sport science due to its ability to provide objective, systematic, and detailed movement evaluation (Rigozzi et al., 2023). Compared with traditional observational approaches, video analysis allows repeated examination of movement execution and supports more transparent and accurate assessment of technical performance (Teferi & Endalew, 2020; Patidar et al., 2026; Rigozzi et al., 2023). Previous studies have shown that video feedback can improve athletes' technical understanding, reflective learning, and self-assessment abilities during skill acquisition processes (Wang & Ni, 2026; Ye & Liu, 2025). Furthermore, recent technological developments, including artificial intelligence-assisted video analysis, have expanded opportunities for automated movement evaluation and technical error detection in sports performance analysis (Kolman et al., 2021; Patidar et al., 2026).

Several previous studies have implemented video analysis methods to evaluate movement quality and technical performance in sports settings (Irawan et al., 2023; Kolman et al., 2021). These approaches have been shown to differentiate technical performance characteristics objectively and identify variations in movement efficiency across skill levels (Brito et al., 2024; Brocherie & Dinu, 2022). In addition, video-based analysis enables micro-analysis of individual movement phases, allowing more systematic identification of technical deficiencies during performance execution (Krizkova et al., 2021).

However, a critical examination of existing literature reveals several important limitations. First, most previous studies have focused primarily on performance enhancement, biomechanical efficiency, or general training outcomes rather than systematically examining technical error characteristics across different technique types and movement phases (Irawan et al., 2023; Krizkova et al., 2021). Second, studies utilising video analysis in racket sports have predominantly targeted expert or competitive-level athletes, with limited attention given to beginner populations such as physical education students (Rigozzi et al., 2023). Third, while qualitative movement analysis frameworks acknowledge that each movement phase contributes differently to overall performance quality (Knudson, 2021), few studies have quantitatively mapped technical error distribution across preparation, execution, and follow-through phases using systematic video-based observation. The gap can be narrowed further by looking at what previous studies have actually measured. Some have focused solely on performance outcomes accuracy, consistency, or match statistics without addressing the underlying movement mechanics that produce those outcomes (Peiris et al., 2025). Others have examined biomechanical parameters in isolation, such as joint angles, segment velocities, or kinetic chains, without linking these measures to a broader instructional or error-based framework (Brito et al., 2024; Brocherie & Dinu, 2022). A third group has investigated the effect of video feedback on learning or skill acquisition in general terms, without specifying where in the movement sequence errors actually occur (Cai et al., 2025; Nijmeijer et al., 2025). None of these approaches, however, has quantitatively mapped technical errors according to the preparation, execution, and follow-through phases of a stroke, and this phase-based gap is precisely what the present study addresses. Nevertheless, limited studies have systematically analysed technical errors in basic tennis skills based on movement phases using video-based assessment, particularly among physical education students. These gaps indicate that phase-based error profiling in basic tennis learning among university students remains empirically underexplored.

This study is grounded in motor learning theory, which emphasises the importance of feedback, movement correction, and repeated practice in the acquisition of motor skills (Hutting et al., 2025; Schlüter et al., 2022). The study also draws upon movement analysis theory, which focuses on systematic biomechanical evaluation of human motion to identify performance deficiencies and movement inefficiencies (Gao & Zhang, 2024; Wang & Ni, 2026). Within this framework, video-based analysis functions as a more objective and systematic assessment tool that facilitates detailed visualisation of movement execution and identification of technical deficits related to biomechanics and motor coordination (Bobrownicki et al., 2019; Jacquier-Bret & Gorce, 2024). In addition, this approach aligns with contemporary technology-orientated learning paradigms in 21st-century physical education, where digital tools are increasingly integrated into instructional and performance evaluation processes (Wang & Ni, 2026).

Recent developments in sport science underscore the growing importance of technology-based movement analysis in performance evaluation and instructional practice (Wang & Ni, 2026; Ye & Liu, 2025). Although prior studies have demonstrated the value of video feedback for improving technical understanding (Irawan et al., 2023; Naskrent et al., 2022) and implicit motor learning outcomes (Nijmeijer et al., 2025). None have specifically applied phase-based video analysis to profile technical errors in basic tennis skills among physical education students. Unlike previous studies that treated movement as a whole-skill unit and reported error occurrence only at the level of the technique itself, the present study introduces a phase-specific technical error profiling framework that integrates systematic video analysis with movement-phase classification (preparation, execution, and follow-through). Rather than evaluating tennis performance as a single, undifferentiated outcome, this framework disaggregates each stroke into its constituent phases, allowing technical errors to be mapped not only to which technique is most error-prone but also to which specific phase within that technique the deficiency occurs. This dual-level mapping is what previous whole-skill or purely biomechanical approaches have not provided. The resulting contribution of this study is therefore twofold: (a) an empirically derived, phase-based error distribution map across basic tennis techniques among physical education students, and (b) a more targeted, diagnostic basis for corrective feedback and instructional design enabling instructors to intervene precisely at the movement phase where errors originate, rather than applying generic, technique-level correction. In this way, the novelty of the present study lies not merely in identifying that phase-based gaps exist, but in producing an actionable diagnostic framework that translates video-based movement analysis directly into targeted pedagogical intervention in physical education settings.

Based on these considerations, this study aims to analyse technical errors in basic tennis skills among physical education students using a video-based analysis approach. Specifically, the study seeks to identify the distribution of technical errors across tennis techniques and movement phases in order to provide empirical evidence supporting the development of more effective, technology-based instructional strategies in tennis learning.

METHODS

Research Design

This study employed a cross-sectional quantitative observational design using a video-based movement analysis approach to identify and compare technical errors across four fundamental tennis techniques (forehand, backhand, serve, and volley) and three movement phases (preparation, execution, and follow-through) among physical education students.

Participants

A total of 36 undergraduate students (mean age = 20.3 ± SD= 1.46) enrolled in the Physical Education Study Programme and registered in a tennis course participated in this study. Participants were selected using purposive sampling to ensure they had prior experience in performing fundamental tennis skills. Most participants had practiced tennis recreationally for at least one semester and were classified as beginner-to-intermediate players based on course participation and instructor evaluation. Purposive sampling was chosen over total sampling because the study required participants who had already acquired a baseline level of tennis technique proficiency; including students without adequate technique exposure would have introduced construct-irrelevant variance into the error-scoring process (Collings et al., 2020; Kibler et al., 2022; Nijmeijer et al., 2025; Wang & Ni, 2026).

The inclusion criteria were: (1) enrollment in the tennis course, (2) prior experience performing fundamental tennis techniques, (3) physical fitness to participate in practical sessions, and (4) willingness to complete all research procedures. Participants were excluded if they: (1) had experienced upper- or lower-limb injuries within the previous six months, (2) were absent during data collection, or (3) failed to complete all movement trials.

The sample size was determined based on an a priori power analysis for one-way ANOVA (e.g., using GPower), assuming a significance level of $\alpha = 0.05$, statistical power of 0.80, and a large effect size, indicating that the required minimum sample size was achieved. (If GPower was not performed, the authors should either conduct and report this analysis or clearly justify the sample size using an appropriate methodological rationale.).

Ethical Considerations

This study was conducted in accordance with the ethical principles of the Declaration of Helsinki, including voluntary participation, confidentiality of participant data, and the right to withdraw at any stage. Ethical approval was obtained from the Health Research Ethics Committee (Komisi Etik Penelitian Kesehatan/KEPK), Faculty of Sport and Health Sciences, Universitas Negeri Gorontalo (Ethical Clearance No. 407/EC/2026). Formal research permission was additionally granted by the Physical Education Study Programme, Universitas Negeri Gorontalo (Permit No. 534/UN47/2/2026). Written informed consent was obtained from all participants prior to data collection.

Research Procedure

Participants performed four fundamental tennis techniques (forehand, backhand, serve, and volley) under standardised conditions during regular course sessions, each completing five repetitions per technique for a total of 720 recorded movement trials (36 × 4 × 5). Recordings were captured using a Sony Alpha 3500 digital camera (18-50 mm lens) at 60 fps, positioned approximately 5 m from participants at a height of 1.45 m, with combined sagittal and frontal views. All sessions were recorded indoors under standardised lighting using the same camera setup throughout data collection.

Footage was analysed frame-by-frame using Kinovea version 0.9.5 (Irawan et al., 2023; Krizkova et al., 2021), evaluating each movement across the preparation, execution, and follow-through phases against predefined biomechanical criteria. A technical error was recorded when a participant showed at least one observable deviation from these criteria in any phase; each trial was coded as containing an error or not, regardless of how many deviations occurred within it.

Instrument

Technical performance was assessed using a video-based observational instrument evaluating four fundamental tennis techniques (forehand, backhand, serve, and volley) across three movement phases: preparation, execution, and follow-through. Each indicator was rated on a four-point ordinal scale, with higher scores reflecting better technical performance; a technical error was defined as any movement deviating from established biomechanical criteria in positioning, racket control, coordination, timing, or follow-through (Bobrownicki et al., 2019; Wang & Ni, 2026). Scoring criteria are presented in **Table 1**.

Prior to data collection, the instrument was content-validated by three experts in tennis coaching and physical education using Aiken's V, achieving a mean V of 0.94 (range 0.78-1.00); two indicators below the 0.80 threshold were revised and retained in the final 16-item set. Recordings were independently scored by two trained observers; inter-rater reliability using Cohen's kappa indicated strong agreement (kappa = 0.82). Operational definitions for each indicator are summarised in **Table 2**.

Table 1. Performance Rating Scale

Score	Category	Interpretation
4	Very Good	Performance meets all technical criteria with no observable errors.
3	Good	Minor technical deviations that do not substantially affect movement execution.
2	Fair	Several technical errors affecting movement quality.
1	Poor	Major technical errors resulting in ineffective movement execution.

Table 2. Operational Definitions of the Observational Instrument

Technique	Movement Phase	Indicator	Operational Definition	Score
Forehand	Preparation	Foot positioning	Feet are positioned shoulder-width apart with the lead foot directed toward the intended stroke before racket movement begins.	1-4
Forehand	Execution	Swing timing	Racket acceleration follows weight transfer and contacts the ball at the optimal point.	1-4
Forehand	Follow-through	Body balance	Body maintains postural stability after completing the stroke without excessive lateral movement.	1-4
Backhand	Preparation	Ready position	The body is balanced with appropriate grip and racket preparation before initiating the stroke.	1-4
Backhand	Execution	Stroke execution	Weight transfer, trunk rotation, and racket movement are coordinated during ball contact.	1-4
Backhand	Follow-through	Recovery	The movement finishes with balanced body posture and controlled racket deceleration.	1-4
Serve	Preparation	Service stance	Feet, body alignment, ball toss, and racket preparation conform to standard serving mechanics.	1-4
Serve	Execution	Ball contact	Ball is struck at the highest reachable point with coordinated body extension and racket acceleration.	1-4
Serve	Follow-through	Landing and balance	The player lands in a balanced position and completes the movement smoothly.	1-4
Volley	Preparation	Ready position	Knees are slightly flexed, racket positioned in front of the body, and eyes focused on the incoming ball.	1-4
Volley	Execution	Ball interception	The racket contacts the ball with minimal backswing while maintaining body stability.	1-4
Volley	Follow-through	Movement completion	The player maintains balance and quickly returns to the ready position.	1-4

Validity and Reliability

The observational instrument was evaluated for content validity and inter-rater reliability prior to data collection to ensure the accuracy and consistency of the assessment. Content validity was established through expert judgment involving three experts in tennis coaching and physical education, who evaluated the relevance, clarity, and representativeness of the assessment indicators. Content validity was quantified using Aiken's V, yielding a mean value of 0.94 (range 0.78-1.00), which exceeded the recommended threshold of 0.80 for satisfactory content validity (Aiken, 1985).

To evaluate scoring consistency, two trained observers independently evaluated all video recordings using the standardized observational instrument. Inter-rater reliability was assessed using Cohen's kappa coefficient, yielding $\kappa = 0.82$. Following the classification proposed by (Landis & Koch, 1977), κ values of 0.61-0.80 indicate substantial agreement and values above 0.80 indicate almost perfect agreement; the obtained value therefore reflects almost perfect agreement between observers, consistent with the more recent benchmarks proposed (Belokurova & Piazza, 2025; Lakens, 2022; McHugh, 2012). The results demonstrated satisfactory levels of both content validity and inter-rater reliability, indicating that the observational instrument was appropriate for assessing technical performance in fundamental tennis skills.

Table 3. Validity and Reliability Criteria

Assessment	Statistical Index	Interpretation Criterion	Reference
Content validity	Aiken's V	V ≥ 0.80 indicates acceptable to excellent content validity	Aiken (1985)
Inter-rater reliability	Cohen's κ	0.61–0.80 = Substantial agreement; 0.81–1.00 = Almost perfect agreement	Landis & Koch (1977)
(Alternative interpretation)	Cohen's κ	Interpretation according to agreement categories	McHugh (2012)

Data Analysis

Composite scores for each tennis technique were calculated by averaging the ratings across all assessment indicators and repeated trials. Although the individual ratings were based on a four-point ordinal scale, the aggregated composite scores were treated as approximately interval-level data because they represented the mean of multiple observations and satisfied the assumptions for parametric analysis (Belokurova & Piazza, 2025).

Prior to inferential analysis, data were screened for outliers using standardised Z-scores ($|Z| > 3.0$). Normality was assessed using the Shapiro-Wilk test, whereas the assumption of sphericity was evaluated using Mauchly's test. Differences in technical performance across the four tennis techniques were analysed using a Repeated Measures ANOVA, followed by Bonferroni-adjusted pairwise comparisons when significant differences were observed. Statistical significance was set at $p < 0.05$, and effect sizes were reported using partial eta squared (η^2p) following the recommendations of (Lakens, 2022).

RESULTS

Participant Characteristics

The demographic characteristics of the study participants are summarised in **Table 4**. These characteristics include participants' gender, age, and prior tennis experience.

Table 4. Participant Characteristics

Characteristic	Category	Frequency (n)	Percentage (%)
Gender	Male	24	66.7%
	Female	12	33.3%
Age	18-20 years	20	55.6%
	21-23 years	16	44.4%
Tennis Experience	< 1 year	14	38.9%
	≥ 1 year	22	61.1%

The sample was predominantly male (66.7%), with most participants aged 18-20 years (55.6%) and having at least one year of tennis experience (61.1%). This distribution reflects the typical composition of students enrolled in the university tennis course from which the sample was drawn.

Descriptive Statistics of Technical Errors

The descriptive statistics of technical error scores for the four fundamental tennis techniques are presented in **Table 5**. Mean scores, standard deviations, and score ranges are reported for each technique.

Table 5. Descriptive Statistics of Basic Tennis Technique Errors

Technique	Mean	SD	Minimum	Maximum
Forehand	3.03	0.43	2.10	4.00
Backhand	2.81	0.46	1.80	3.80
Serve	3.28	0.39	2.40	4.00
Volley	1.46	0.32	1.00	2.30

As presented in **Table 5**, the serve recorded the highest mean technical error score (M = 3.28, SD = 0.39), followed by the forehand (M = 3.03, SD = 0.43) and backhand (M = 2.81, SD = 0.46). The volley demonstrated the lowest mean score (M = 1.46, SD = 0.32). Standard deviations ranged from 0.32 to 0.46, indicating relatively consistent performance across participants within each technique.

Distribution of Technical Errors

Based on Technique

The frequency distribution of technical errors across the four tennis techniques is presented in **Table 6**. Error frequencies were calculated from all recorded trials containing at least one technical error.

Table 6. Frequency Distribution of Technical Errors

Technique	Frequency	Percentage (%)
Forehand	102	28.3
Backhand	95	26.4
Serve	112	31.1
Volley	51	14.2
Total	360	100

A total of 720 movement trials were analysed, of which 360 trials contained at least one technical error. As shown in **Table 6**, the serve accounted for the largest proportion of technical errors (31.1%), followed by the forehand (28.3%) and backhand (26.4%). The volley contributed the smallest proportion of technical errors (14.2%).

Distribution by Movement Phase

Table 7 summarises the distribution of technical errors across the three movement phases. The frequencies and percentages of errors are presented for the preparation, execution, and follow-through phases.

Table 7. Distribution of Technical Errors by Movement Phase

Movement Phase	Frequency	Percentage (%)
Preparation	98	27.2
Execution	162	45.0
Follow-through	100	27.8
Total	360	100

As shown in **Table 7**, the execution phase accounted for the largest proportion of technical errors (45.0%). The preparation and follow-through phases contributed 27.2% and 27.8% of the total recorded errors, respectively.

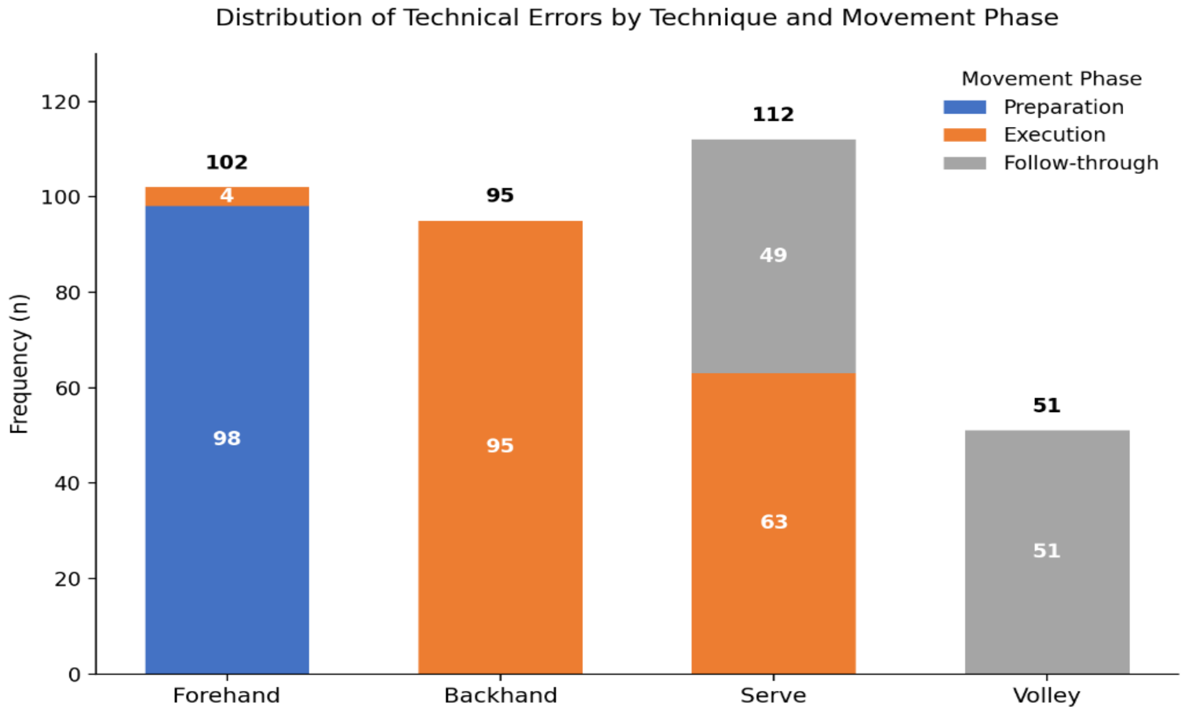

Figure 1. Distribution of Technical Errors by Technique and Movement Phase

Figure 1 shows that the phase contributing most errors differed by technique rather than following a uniform pattern. Forehand errors were concentrated in the preparation phase (98 of 102 errors), backhand errors occurred almost exclusively during execution (95 of 95), and volley errors were confined to the follow-through phase (51 of 51). The serve was the only technique with errors distributed across two phases, split between execution (63) and follow-through (49). These results indicate that the execution phase was not uniformly the primary source of error across techniques, but rather that each technique carried a distinct, phase-specific error signature.

Inferential Analysis

Prior to inferential analysis, the assumptions required for parametric testing were examined. The results of the normality assessment using the Shapiro-Wilk test are presented in **Table 8**.

Table 8. Shapiro-Wilk Test of Normality

Technique	Statistic	p-value
Forehand	0.995	1.000
Backhand	0.995	1.000
Serve	0.988	0.957
Volley	0.959	0.195

The Shapiro-Wilk test indicated that the distribution of technical error scores for all four techniques did not significantly deviate from normality (all $p > 0.05$), supporting the assumption of normality. Homogeneity of variance was subsequently evaluated before conducting the inferential analysis. The results of Levene's test are presented in **Table 9.**

Table 9. Levene's Test for Homogeneity of Variance

Levene Statistic	df1	df2	p-value
1.534	3	140	0.208

Levene's test produced a non-significant result (p = 0.208), indicating that the assumption of homogeneity of variance was satisfied. After the statistical assumptions were confirmed, inferential analysis was conducted to examine differences in technical error scores among the four tennis techniques. The results are presented in **Table 10**.

Table 10. One-Way ANOVA Results

Variable	F	p-value	η^2	Effect Size
Technique Scores	146.706	< 0.001	0.76	Large

The analysis revealed a statistically significant difference in technical error scores among the four tennis techniques ($F = 146.706$, $p < 0.001$, $\eta^2 = 0.76$), indicating a large effect of technique types on technical error scores. Post hoc comparisons using Tukey's HSD indicated that the serve produced significantly higher technical error scores than the volley (mean difference = 1.81, SE = 0.067, $p < 0.001$, 95% CI [1.57, 2.06]). No significant difference was observed between the forehand and backhand techniques (mean difference = 0.23, SE = 0.067, $p = 0.086$, 95% CI [-0.02, 0.47]). Overall, the results indicate significant differences in technical error scores among the four fundamental tennis techniques. The serve demonstrated the highest technical error scores, whereas the volley exhibited the lowest.

DISCUSSION

This study examined technical errors in four fundamental tennis techniques (forehand, backhand, serve, and volley) among physical education students using video-based movement analysis. Technical error levels differed significantly by technique type and by movement phase. The serve produced the highest error frequency among the four techniques, while the volley produced the lowest. Across movement phases, execution accounted for the largest share of errors (45%), followed by follow-through and preparation. These patterns were not uniform across techniques: each technique carried a distinct, phase-specific error signature rather than errors clustering predictably in the same phase across all techniques.

One-way ANOVA revealed significant differences in technical error levels across the four tennis techniques ($F = 146.706$, $p < 0.001$, $\eta^2 = 0.76$), indicating that each technique presents distinct coordinative and biomechanical demands. The elevated error frequency in the serve is consistent with its comparatively greater coordinative and biomechanical demand. Serve execution requires sequential coordination across the ball toss, trunk rotation, lower-body stabilisation, arm acceleration, and racket–ball contact timing — a longer and more tightly sequenced kinetic chain than the other three techniques. Prior biomechanical work on the tennis serve has similarly emphasised its dependence on coordinated kinetic-chain movement and synchronised segmental action (Genevois et al., 2020; Irawan et al., 2023; Jacquier-Bret & Gorce, 2024), which supports interpreting the serve's error rate as a function of coordinative complexity rather than any single isolated fault.

The concentration of errors in the execution phase is likewise explainable biomechanically. Execution is the point at which force generated at the larger, proximal segments (legs and trunk) must be transferred sequentially through the shoulder, elbow, and wrist to the racket head — the proximal-to-distal sequencing principle. A timing fault introduced earlier in this chain is not self-correcting; it propagates forward and is amplified at ball contact, which is consistent with execution errors being both the most frequent and the most consequential for stroke accuracy observed here.

From a motor learning perspective, these patterns fit Fitts and Posner's three-stage model: learners in the early cognitive and associative stages — the likely stage for most participants in this study — rely on conscious attention to execute movement, which leaves less attentional capacity available during the technically demanding execution phase and increases the likelihood of coordination errors precisely where they were observed. The findings are also consistent with Gentile's two-stage model of motor learning: the relatively low error rate in preparation suggests participants had grasped the general idea of each movement, while the concentration of errors in execution suggests they had not yet refined the fine motor adjustments needed for consistent, adaptable performance. Taken together, the error pattern observed here reflects a coordinative-demand mechanism — techniques and phases requiring simultaneous integration of multiple body segments were consistently the most error-prone — rather than a single technique being uniformly "harder" in every respect.

The present findings are broadly consistent with, and extend, prior technology-assisted performance-analysis research in racket sports, with some points of both agreement and divergence. Peiris et al. (2025) linked unforced technical errors to reduced match performance, supporting the practical relevance of systematically identifying error patterns rather than treating them as incidental — consistent with the phase-specific error signatures identified here. Krizkova et al. (2021) found that micro-analysis of individual movement phases through video enables more precise identification of technical deficiencies than whole-movement judgements; the present study's phase-level error breakdown directly mirrors this conclusion. Kolman et al. (2021) argued that progressive skill development in tennis requires structured technical learning rather than repetitive practice alone, which is consistent with the present finding that errors clustered in specific, identifiable phases rather than occurring diffusely across the whole movement.

Rigozzi et al. (2023) noted that wearable and video-based motion-analysis technologies have been applied predominantly to competitive or expert athletes. The present study diverges from this pattern by applying phase-based video analysis to a beginner, physical-education-student population, and finds that the same diagnostic approach remains feasible and informative outside the competitive-athlete contexts where it has typically been used. Physical education teachers, the finding that errors concentrate in technique-specific phases (preparation for forehand, execution for backhand, execution and follow-through for serve, follow-through for volley) suggests that instructional cues should be timed to the phase where each technique is most error-prone, rather than applying generic, whole-movement corrections. For example, forehand instruction may benefit from added emphasis on preparatory foot and body positioning, whereas backhand and serve instruction may benefit more from cues delivered during the execution phase itself (e.g., verbal timing cues during racket-ball contact). For coaches working with beginner-to-intermediate players, the serve's distribution of errors across both execution and follow-through suggests that serve practice should isolate these two phases separately (e.g., shadow-swing drills focusing on contact point, followed by separate balance-and-landing drills) rather than practicing the full serve motion repeatedly without phase-specific feedback. Lecturers and researchers in physical education teacher education, the video-based phase-analysis method demonstrated here offers a low-cost, replicable tool (a standard camera plus Kinovea) that can be incorporated into methods courses to train pre-service teachers in structured, criterion-referenced movement observation, rather than relying on holistic, real-time visual judgement alone. Students, the phase-specific error findings suggest that self-review of one's own recorded performance — pausing at the execution phase in particular — may be a more targeted self-correction strategy than reviewing the stroke as a whole.

This study offers three methodological strengths. First, phase-level error analysis (preparation, execution, follow-through) allowed errors to be attributed to a specific stage of movement rather than to the technique as a whole, which produced the phase-specific findings reported above. Second, video-based analysis allowed each trial to be replayed and paused, enabling reliable phase-by-phase judgment rather than a single holistic real-time impression. Third, the use of two independent observers scoring from a permanent video record allowed inter-rater reliability to be quantified (Cohen's κ = 0.82), which live, single-observer assessment cannot provide. This study has several limitations. The sample was drawn from physical education students at a single institution, which may limit generalisability to other populations, age groups, or competitive tennis players. Error scoring relied on manual, observer-based video analysis rather than advanced biomechanical tools such as 3D motion capture or kinematic analysis software, which may constrain the precision of error detection relative to marker-based methods. The descriptive design limits causal interpretation of the relationship between video-based analysis and skill improvement outcomes. In addition, because all participants performed all four techniques, the design was inherently repeated-measures in nature; although One-way ANOVA was used to compare mean error levels across technique categories, the potential non-independence introduced by using the same participants across techniques is acknowledged as a methodological limitation.

Future studies are recommended to: (1) involve larger and more diverse participant samples across multiple institutions; (2) adopt experimental or quasi-experimental intervention designs to test the causal effect of phase-based, video-informed feedback on error reduction; (3) incorporate markerless motion capture or AI-based pose-estimation technology (e.g., OpenPose or MediaPipe) alongside software such as Kinovea or Dartfish to increase measurement precision; and (4) examine playing-experience level as a moderating variable through longitudinal or comparative designs.

CONCLUSION

This study demonstrated that technical error patterns in fundamental tennis skills differed according to both technique type and movement phase among undergraduate physical education students. The serve produced the highest technical error scores and frequency of errors, whereas the execution phase accounted for the greatest proportion of technical errors. These findings indicate that technical performance varies across fundamental tennis techniques and movement phases, highlighting specific stages that require greater instructional attention.

This study contributes to the existing literature by demonstrating the usefulness of video-based phase analysis for identifying technique-specific and phase-specific technical errors in beginner tennis performers. This approach provides a more detailed evaluation of movement performance than conventional whole-technique observation and offers objective information that can support instructional decision-making.

From a practical perspective, the findings suggest that tennis instruction should incorporate phase-specific feedback, particularly during the execution phase, and use video-based movement analysis to facilitate objective assessment and corrective feedback. Future studies should validate these findings using larger and more diverse samples and evaluate the effectiveness of video-assisted interventions through experimental or longitudinal research designs.

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CONFLICT OF INTEREST

The authors declare no competing financial or non-financial interests.

AI DISCLOSURE STATEMENT

During the preparation of this manuscript, the authors used generative artificial intelligence (AI) tools to assist with language refinement, sentence structure, and readability. All AI-assisted content was reviewed and verified by the authors, who remain responsible for the accuracy, originality, and final content of the manuscript.

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