Research Square

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Format-Specific Atrial Depolarization in Tennis: Wearable Electrocardiography and AI- Assisted P-Wave Analysis in Collegiate Players

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Abstract

Background

Tennis imposes intermittent and variable physiological demands that may influence atrial depolarization, yet electrophysiological responses across different play formats remain poorly understood. Wearable electrocardiography provides an opportunity to examine in-situ P-wave dynamics as indicators of atrial electrical activity during tennis-specific exercise. This study investigated format-specific atrial depolarization patterns during singles match play, doubles match play, a 12-min Cooper run, and a tennis-specific technical endurance drill in collegiate tennis players.

Methods

Twelve trained male collegiate tennis players (21.4 ± 3.2 years) completed four exercise protocols on separate days: singles match play, doubles match play, a 12-min Cooper run, and a tennis-specific technical endurance drill. A single-lead wearable ECG patch (256 Hz) continuously recorded cardiac electrical activity throughout each protocol. P-wave onset, peak, and offset were identified using an attention U-Net–assisted segmentation algorithm with derivative-based refinement. Derived indices included P-wave duration, peak amplitude, and voltage–time integrals of the initial (front) and terminal (rear) depolarization phases. Winner–loser differences during singles and doubles match play were analyzed using independent-samples t-tests and Hedges' g effect sizes.

Results

In singles match play, winners demonstrated a shorter P-wave duration than losers (91.27 ± 4.23 vs. 99.09 ± 4.83 ms; $p = 0.014$; $g = -1.59$). In doubles match play, winners exhibited a smaller initial (front) area (0.42 ± 0.13 vs. 0.66 ± 0.10 mV·ms; $p = 0.005$; $g = -1.90$) and lower peak amplitude (0.17 ± 0.02 vs. 0.20 ± 0.02 mV; $p = 0.045$; $g = -1.22$), whereas P-wave duration did not differ significantly between groups. During the Cooper run and tennis-specific technical endurance test, mean P-wave duration and initial (front) area values were greater than those observed during match play.

Conclusions

Atrial depolarization exhibited task-specific characteristics across different tennis exercise formats. Faster atrial depolarization timing distinguished winners during singles match play, whereas reduced early-phase atrial electrical activity characterized winners during doubles match play. These findings support the feasibility of combining wearable single-lead ECG monitoring with automated P-wave analysis for field-based electrophysiological profiling in tennis athletes.

Introduction

Tennis is a high-intensity intermittent sport characterized by repeated short bursts of maximal effort, rapid directional changes, and intermittent recovery periods, placing substantial and fluctuating demands on the cardiovascular system[1–2]. In recent years, increasing attention has been directed toward athlete cardiac health and exercise-induced electrophysiological changes. Among electrocardiographic markers, P-wave parameters are recognized as key indicators of atrial depolarization and conduction properties, offering valuable insights into atrial loading, conduction abnormalities, and the potential risk of atrial arrhythmias[3–4]. In addition, maximal oxygen uptake (VO_2max) testing and tennis-specific endurance assessments are widely applied to evaluate cardiovascular fitness and tennis-specific performance, providing important measures of physiological capacity and adaptability under different workloads[5–7].

Previous research has predominantly examined the effects of endurance-based sports such as long-distance running, cycling, and triathlon on cardiac structure and function[8]. In contrast, limited evidence is available regarding the atrial electrophysiology of high-intensity intermittent sports like tennis[9–10]. While some studies have investigated heart rate responses and autonomic regulation during tennis play[11–14], systematic analyses of P-wave characteristics remain scarce. Furthermore, little is known about how atrial electrical responses differ between winning and losing players, or how consistent these patterns are across various competitive and laboratory-based testing scenarios.

Given the unique workload profile of tennis, applying multiple testing modalities may provide a more comprehensive understanding of atrial electrophysiological responses under different physiological demands[15–17]. Therefore, the present study aimed to examine P-wave characteristics in competitive tennis players across four distinct workload conditions—singles match-play, doubles match-play, VO_2max testing, and a tennis-specific endurance test—and to compare responses between winners and losers. This multi-scenario approach was designed to identify consistent patterns of atrial activity and evaluate the feasibility of using such assessments for athlete cardiac monitoring and performance evaluation.

Methods

Study Design

This repeated-measures study examined four distinct workload conditions: (1) a singles match-play match, (2) a doubles match-play match, (3) a 12-min Cooper run to estimate VO_2max, and (4) a tennis-specific technical endurance test. The order of conditions was counterbalanced across participants with a washout period of at least 48 hours to minimize carryover effects and ensure adequate recovery. All sessions were conducted under comparable environmental conditions, with ambient temperature and relative humidity recorded at the start and end of each test.

Participants

Twelve male collegiate tennis players (mean age: 21.42 ± 3.22 years; range: 18–26 years) were recruited for this study. Inclusion criteria were: (1) a minimum of 6 years of structured tennis training, (2) regular engagement in organized domestic age-group competitions, (3) participation in structured training sessions ≥ 3 times per week, (4) absence of known cardiovascular or metabolic disorders, and (5) ability to complete high-intensity exercise protocols. Exclusion criteria included any history of congenital heart disease, clinically documented arrhythmias, or musculoskeletal injuries that could limit exercise performance. Eligibility was confirmed through pre-experimental questionnaires and interviews combined with detailed medical history assessments. All participants provided written informed consent.

Baseline Cardiac Assessment

Prior to the exercise tests, all participants underwent a comprehensive baseline cardiac evaluation. Transthoracic echocardiography was performed using a clinically validated ultrasound system (EPIQ-CVx, Philips Healthcare, Andover, MA, USA) equipped with an X7-2 transducer to assess cardiac structure and function. All examinations were conducted by an experienced cardiologist in accordance with standardized clinical protocols. Written informed consent was obtained from all participants prior to the assessment.

Experimental Protocols

1. Match Protocol: Singles and Doubles

All participants completed one singles match-play and one doubles match-play match on outdoor clay courts, played under International Tennis Federation (ITF) regulations with a one-set format (first to 6 games; 10-point tiebreak at 6–6). Singles were scheduled at 09:00, and doubles at 09:00 on the following day to ensure overnight recovery. Opponents of comparable skill levels were paired by a nationally certified coach. A standardized 5-min dynamic warm-up preceded each match. Changeovers followed official timing; participants were allowed water or sports beverages during changeovers to minimize dehydration. To reproduce competitive intensity, coaches and research staff provided standardized verbal encouragement.

Environmental conditions (ambient temperature, relative humidity) were recorded at the start and end of each match; sessions took place within 25–30°C and 55–70% RH.

2. VO_2max Testing

Maximal aerobic capacity was estimated using the Cooper 12-minute run on a 400 m outdoor track under standardized conditions (temperature 24–28°C, humidity 50–65% RH), supervised by the same research team. After receiving standardized instructions, participants completed a 15-minute dynamic

warm-up, then ran continuously for 12 minutes to maximize distance, with verbal encouragement at 3, 6, and 9 minutes. Total distance (including the final partial lap) was recorded, and VO_2max was estimated using the Cooper equation:

VO2max (ml·kg − 1·min − 1) = 22.351×distance (km) − 11.288.

3. Tennis-Specific Technical Endurance Drill

A tennis-specific technical endurance test adapted from Baiget et al. (2015) was employed[18]. Balls were fed manually by a nationally certified coach (Slazenger WIMBLEDON balls). The drill alternated forehand and backhand groundstrokes directed to within ~ 2 m of each baseline corner (Fig. 1). Ball frequency started at 9 balls·min^{-1} and increased by 2 balls every 2 minutes until termination.

Technical efficacy (TE) was assessed by two criteria:

(1) Accuracy—the ball had to land within a 3.1 × 4.5 m target zone located 1 m behind the service line and 1 m to either side of the center mark;

(2) Power—shots landing within the target zone had to cross the Power Line (5 m beyond the baseline, 4 m inside the singles sideline) before the second bounce.

The test terminated when TE criteria were no longer met, upon voluntary cessation, or when heart rate exceeded 95% of estimated HRmax, where HRmax = 208 − 0.7 × age (Tanaka et al.).

ECG acquisition and processing

A single-lead wearable ECG patch (SIGKNOW, Taiwan) was affixed at the right parasternal 2nd intercostal space and oriented toward the left ventricular apex, forming a quasi-vector directed anteroinferiorly. Signals were continuously sampled at 256 Hz from 10 min before warm-up, throughout each test (matches/drills/runs), and until 10 min post-exercise recovery. Signals underwent band-pass filtering (0.5–40 Hz), baseline-wander removal, and wavelet-based denoising to attenuate motion artefacts. Segments with distortion (e.g., excessive movement or electrode detachment) were identified by amplitude/variance thresholds and excluded.

P-wave onsets, peaks, and offsets were delineated using an attention U-Net–assisted algorithm with derivative-based refinement. For morphology, each P-wave was partitioned into an initial (front) and a terminal (rear) segment relative to the P-peak, representing early and terminal atrial depolarization phases, respectively (We avoid the term repolarization for P-wave analyses and instead refer to the terminal atrial depolarization segment). Beat-wise indices included P-wave duration (ms), peak amplitude (mV), and P-wave voltage–time integrals for the front and rear segments (mV·ms). Indices were averaged per participant per condition.

Outcome Definition and Grouping (match conditions)

Outcome Definition and Grouping (match conditions)
For singles and doubles, participants were classified as winner or loser based on match outcome. P-wave indices were summarized at the participant level within each match condition and compared between groups.

Statistical Analysis

Data are presented as mean ± SD. Shapiro–Wilk and Levene's tests assessed normality and homogeneity. For singles and doubles, independent-samples t-tests compared winners vs. losers for each index; Hedges' g with 95% confidence intervals quantified effect sizes. Exploratory linear mixed-effects models (participant as a random intercept) were considered to account for repeated measures, with ambient temperature and relative humidity as covariates in sensitivity analyses. To address multiplicity across four conditions × multiple ECG indices, p-values were adjusted using the Benjamini–Hochberg false discovery rate (q = 0.05). Two-tailed α = 0.05.

Results

Participant Characteristics

Baseline characteristics of the 12 male collegiate tennis players are summarized in Table 1. The cohort had a mean age of 21.42 ± 3.22 years and a mean training history of 6.50 ± 3.18 years. Anthropometric indices (height, weight, BMI, waist and hip circumferences, and waist-to-hip ratio) were within the expected range for trained young adult players.

Table 1
Baseline characteristics of the study participants

Variable	**Mean ± SD (n = 12)**
Age (years)	21.42 ± 3.22
Height (cm)	174.00 ± 3.84
Weight (Kg)	69.00 ± 6.03
BMI (Kg/m²)	22.80 ± 1.93
Waist circumference (cm)	79.67 ± 5.28
Hip circumference (cm)	99.12 ± 4.22
Waist-to-hip ratio (WHR)	0.80 ± 0.04
Training history (years)	6.50 ± 3.18
Values are presented as mean ± SD.	

P-wave Responses during Simulated Tennis Match Play

Atrial electrical behavior during simulated match play was evaluated using P-wave morphology as an index of atrial activation. Singles and doubles were analyzed separately to compare cardiac demands under distinct competitive formats. P-wave responses during simulated singles and doubles match play are illustrated in Fig. 2 and Fig. 3, respectively.

Singles

Compared with losers, winners demonstrated a significantly shorter P-wave duration (91.27 ± 4.23 vs. 99.09 ± 4.83 ms; p = 0.014; Hedges' g = − 1.59, 95% CI − 2.85 to − 0.33). Peak amplitude was comparable between groups (0.18 ± 0.06 vs. 0.20 ± 0.02 mV; p = 0.601; Hedges' g = − 0.29). Initial (front) area did not differ significantly (0.43 ± 0.11 vs. 0.55 ± 0.11 mV·ms; p = 0.099; Hedges' g = − 0.97, 95% CI − 2.10 to 0.16). Similarly, no significant difference was observed in terminal (rear) area (− 6.43 ± 1.05 vs. −5.80 ± 1.17 mV·ms; p = 0.343; Hedges' g = − 0.53, 95% CI − 1.60 to 0.54). These findings are illustrated in Fig. 2.

Doubles

P-wave duration did not differ significantly between winners and losers (103.04 ± 4.23 vs. 109.65 ± 8.98 ms; p = 0.134; Hedges' g = − 0.87, 95% CI − 1.98 to 0.24). Winners exhibited a lower peak amplitude (0.17 ± 0.02 vs. 0.20 ± 0.02 mV; p = 0.045; Hedges' g = − 1.22, 95% CI − 2.40 to − 0.05) and a smaller initial (front) area (0.42 ± 0.13 vs. 0.66 ± 0.10 mV·ms; p = 0.005; Hedges' g = − 1.90, 95% CI − 3.24 to − 0.57). Terminal (rear) area did not differ significantly between groups (− 6.71 ± 2.90 vs. −4.82 ± 2.17 mV·ms; p = 0.228; Hedges' g = − 0.68, 95% CI − 1.77 to 0.40). These findings are illustrated in Fig. 3.

VO_2max (12-min Cooper run; see Table 2)

Table 2 summarizes the overall P-wave metrics obtained during the 12-min Cooper run. Across all participants (N = 12), mean P-wave duration was 109.65 ± 6.68 ms, peak amplitude was 0.22 ± 0.03 mV, initial (front) area was 0.57 ± 0.09 mV·ms, and terminal (rear) area was − 5.16 ± 1.24 mV·ms. Values are presented as mean ± SD.

Table 2
P-wave indices during the 12-min Cooper run.

Index	Overall mean ± SD (N = 12)
P-wave duration (ms)	109.65 ± 6.68
Peak amplitude (mV)	0.22 ± 0.03
Initial (front) area (mV·ms)	0.57 ± 0.09
Terminal (rear) area (mV·ms)	-5.16 ± 1.24
Values are presented as mean ± SD.	

P-wave Characteristics During the Tennis-Specific Technical Endurance Test

Table 3 summarizes the overall P-wave metrics obtained during the tennis-specific technical endurance test. Across all participants (N = 12), mean P-wave duration was 101.74 ± 5.80 ms, peak amplitude was 0.19 ± 0.03 mV, initial (front) area was 0.55 ± 0.10 mV·ms, and terminal (rear) area was − 4.86 ± 1.38 mV·ms. Values are presented as mean ± SD.

Table 3
P-wave indices during the tennis-specific technical endurance test.

Index	Overall mean ± SD (N = 12)
P-wave duration (ms)	101.74 ± 5.80
Peak amplitude (mV)	0.19 ± 0.03
Initial (front) area (mV·ms)	0.55 ± 0.10
Terminal (rear) area (mV·ms)	−4.86 ± 1.38
Values are presented as mean ± SD.	

Discussion

Principal findings

This study employed a long-duration wearable ECG patch (SIGKNOW, single-lead, 256 Hz) to quantify beat-wise P-wave morphology in trained collegiate tennis players during singles and doubles match play, as well as during two standardized field tests (12-min Cooper VO_2max and a tennis-specific technical endurance drill). Three principal findings emerged. First, during singles match play, winners exhibited a shorter P-wave duration than losers (Hedges' g = − 1.59, 95% CI − 2.85 to − 0.33; p = 0.014), indicating faster atrial depolarization. Second, during doubles match play, winners demonstrated a smaller initial (front) P-wave area (g = − 1.90, 95% CI − 3.24 to − 0.57; p = 0.005) and a lower peak amplitude (g = − 1.22, 95% CI − 2.40 to − 0.05; p = 0.045), suggesting reduced early-phase atrial electrical activity. Third, terminal (rear) area did not differ significantly between winners and losers in either match format.

For exercise modalities without a winner–loser classification, overall mean values obtained during the VO_2max test and tennis-specific technical endurance drill demonstrated longer P-wave duration and larger initial (front) area values than those observed during match play. These findings suggest that continuous aerobic exercise and prolonged tennis-specific exertion may impose greater atrial activation demands than competitive match play.

Physiological interpretation and context

P-wave duration reflects the overall timing of intra- and inter-atrial conduction[19]. In singles, the shorter duration observed in winners may indicate more synchronized atrial depolarization and/or reduced conduction delay[20–21] under the technical–tactical and autonomic demands of the format[22–23]. It may also reflect a more favorable instantaneous atrial loading state[24–25]. Because heart-rate variability or structural indices (e.g., echocardiography) were not collected, these are interpretative, not causal, explanations.

In doubles, the combination of a lower peak amplitude and smaller initial (front) area in winners can be interpreted as a reduction in the integrated and peak electrical activity during the early depolarization phase[26–27]. Candidate mechanisms include: (i) a smaller effective electrical contribution from simultaneously depolarizing atrial tissue (greater synchronization with less “spread”) [26–27]. (ii) transient orientation of the depolarization vector relative to the patch axis (posture, arm/torso kinematics) that yields lower recorded amplitude in a single-lead configuration [28–29], and (iii) format-specific pacing with more frequent micro-recoveries that modulate preload/afterload and autonomic balance [30–32]. It should be noted that initial and terminal denote temporal phases relative to the P-peak, not chamber identity; no right- vs left-atrial attribution is implied with a single-lead recording [26, 28].

Taken together, these findings suggest task-specific modulation of atrial depolarization, with singles match play characterized by faster atrial depolarization timing and doubles match play characterized by reduced early-phase electrical activity. However, these interpretations should be considered within the constraints of a single-lead wearable ECG recorded under field conditions.

Task specificity: singles versus doubles

Singles tennis typically requires greater court coverage, longer rallies, and a higher individual decision-making burden [33], whereas doubles emphasizes shorter exchanges, net play, and cooperative positioning between partners[34–36]. Consistent with these differing task demands, the performance-associated P-wave patterns were format-specific. In singles match play, winners exhibited faster atrial depolarization timing, reflected by a shorter P-wave duration. In contrast, doubles winners demonstrated reduced early-phase atrial electrical activity, characterized by a smaller initial (front) area and lower peak amplitude. These findings suggest that distinct competitive formats may impose different electrophysiological demands on atrial activation. [37], This pattern may reflect differences in autonomic regulation, cardiac loading conditions, and energetic allocation between singles and doubles play[30, 3, 38]; However, because heart rate variability and structural cardiac measurements were not obtained concurrently, these interpretations should be considered speculative rather than causal.

Prior studies have demonstrated that exercise intensity, endurance load, and competitive context can influence atrial conduction and P-wave morphology[39–41]. The present study extends this literature in three ways. First, prolonged in-field ECG monitoring was performed during ecologically valid tennis-specific tasks [42] Second, an attention U-Net–assisted segmentation approach was used to characterize the P-wave and quantify its initial and terminal temporal phases [43–46] Third, format-specific

electrophysiological responses were compared between singles and doubles match play within the same cohort. The shorter P-wave duration observed in singles winners is consistent with previous findings linking more efficient atrial conduction to favorable physiological and performance-related states[20–21] .In contrast, the smaller initial (front) area observed in doubles winners appears to represent a novel finding in the tennis literature. Although P-wave area has previously been proposed as a quantitative marker of atrial electrical remodeling[27] the present findings suggest that match format may also influence specific features of atrial depolarization, highlighting the task-specific nature of cardiac electrophysiological responses during tennis competition [33–36] .

Methodological considerations and limitations

Several limitations should be acknowledged. First, P-wave morphology was derived from a single-lead wearable ECG system. Therefore, the observed differences should be interpreted as temporal-phase characteristics of atrial depolarization rather than chamber-specific phenomena. In addition, instantaneous changes in depolarization vector orientation, posture, and upper-body movement may have influenced the recorded amplitudes.

Second, the study cohort consisted exclusively of male collegiate tennis players participating in simulated match-play conditions. Consequently, caution is warranted when generalizing these findings to female athletes, different age groups, recreational players, or official competitive settings.

Third, although signal-quality control procedures were applied, respiration, body movement, and other sources of motion artefact may still have affected waveform morphology. Accordingly, residual measurement error cannot be completely excluded.

Fourth, for the VO_2max and tennis-specific technical endurance tests, only overall mean values were analyzed because no winner–loser classification was applicable to these exercise modalities.

Finally, match outcome (winner vs. loser) was used as a proxy measure of performance. This classification may reflect differences in tactical strategy, fatigue status, hydration, psychological factors, and other unmeasured influences. Although environmental conditions and fluid intake were standardized as much as possible, residual confounding cannot be excluded.

Practical implications

The present findings suggest that P-wave duration and early-phase P-wave characteristics (initial area and peak amplitude) may have potential utility as field-based indicators of physiological responses to different tennis match formats. With appropriate individualized baseline measurements, singles match play may be more effectively monitored through changes in P-wave duration, whereas doubles match play may be more sensitive to alterations in early-phase P-wave magnitude. Furthermore, the successful implementation of prolonged single-lead wearable ECG monitoring under real-world tennis conditions supports the feasibility of integrating wearable cardiac monitoring into athlete training, recovery assessment, and longitudinal performance surveillance.

Future directions

We recommend extending the work to larger, sex-balanced cohorts and official competitive matches; integrating HRV, respiratory metrics, and echocardiographic indices of atrial structure and function; conducting longitudinal and within-athlete analyses; and validating the algorithmic segmentation against multi-lead annotations. Incorporating technical–tactical variables (e.g., rally length, serve/return patterns) into the models may further clarify links between match structure and P-wave features.

Conclusion

In collegiate tennis players, winners exhibited shorter atrial depolarization timing during singles match play, reflected by a shorter P-wave duration, whereas doubles winners demonstrated reduced early-phase atrial electrical activity, characterized by a smaller initial (front) area and lower peak amplitude. No significant differences were observed in terminal (rear) area between winners and losers in either match format. Additionally, the VO_2max and tennis-specific technical endurance tests were characterized by longer P-wave duration and larger initial area values than those observed during match play. Collectively, these findings suggest task-specific modulation of atrial depolarization in competitive tennis and support the feasibility of wearable single-lead ECG for field-based electrophysiological profiling and athlete monitoring.

Abbreviations

AI
artificial intelligence
CI
confidence interval
ECG
electrocardiography
FDR
false discovery rate
HR
heart rate
HRmax
maximal heart rate
ITF
International Tennis Federation
mV
millivolt
ms
millisecond
P-wave

atrial depolarization wave
RH
relative humidity
SD
standard deviation
TE
technical efficacy
U-Net
convolutional neural network architecture for image segmentation
VO_2max
maximal oxygen consumption

Declarations

Ethics approval

This study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Kaohsiung Medical University Hospital Institutional Review Board (KMUHIRB-E(I)-20220234).

Clinical trial number: not applicable.

Consent to Participate

Informed consent was obtained from all individual participants included in the study.

Consent to Publish

The authors affirm that human research participants provided informed consent for the publication of data.

Availability of data and materials

The datasets generated and analyzed during this study contain sensitive personal health information and are therefore not publicly available. All data are securely stored within the controlled data repository of Kaohsiung Medical University. Data may be made available from the corresponding author upon reasonable request and subject to institutional data access regulations.

Conflict of interest

The authors have no relevant financial or non-financial interests to disclose.

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Authors' contributions

All authors contributed to the study and approved the final manuscript.

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Figures

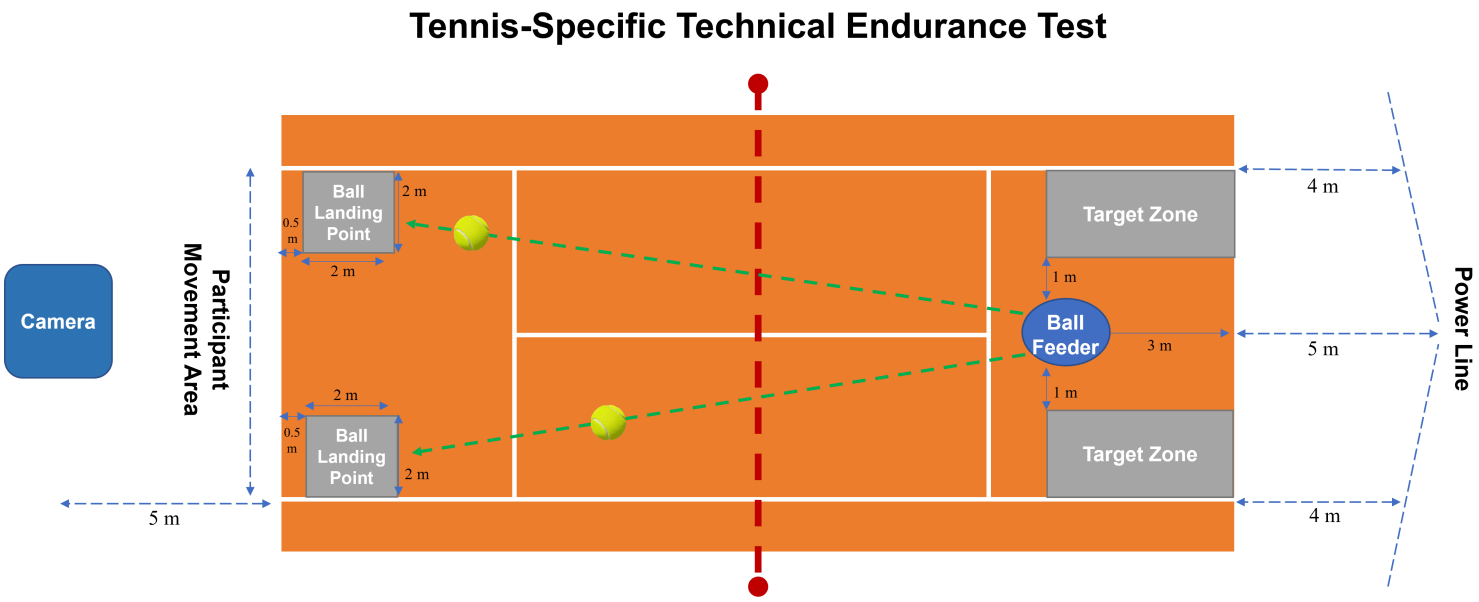


Figure 1

Schematic representation of the tennis-specific technical endurance test. Balls were fed by a coach while participants alternated forehand and backhand groundstrokes toward the designated target zones. Technical efficacy was evaluated based on shot accuracy and whether the ball crossed the Power Line before the second bounce.

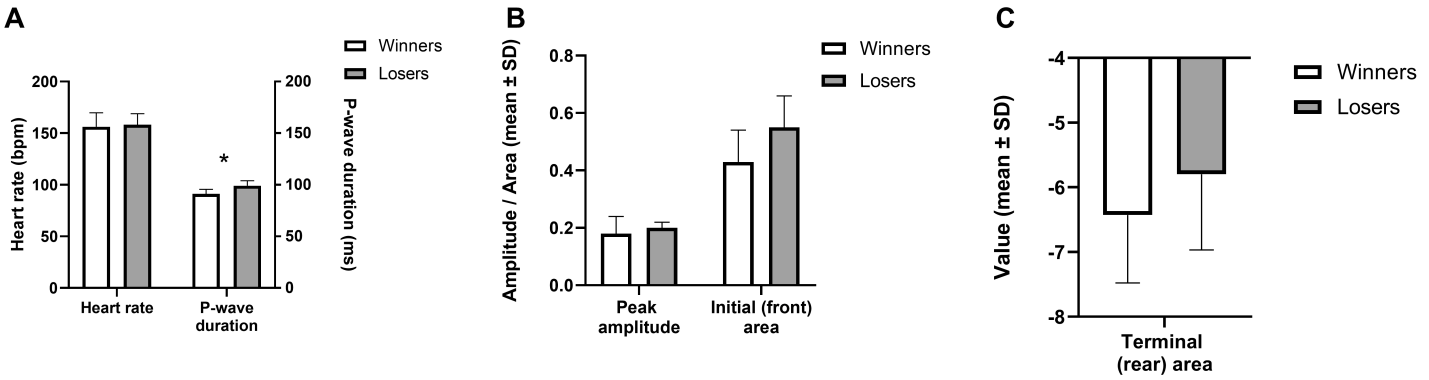


Figure 2

P-wave characteristics during simulated singles match play. (A) Comparison of heart rate and P-wave duration between winners and losers. (B) Comparison of P-wave peak amplitude and initial (front) area between winners and losers. (C) Comparison of P-wave terminal (rear) area between winners and losers. Values are presented as mean ± SD. *p < 0.05 versus losers.

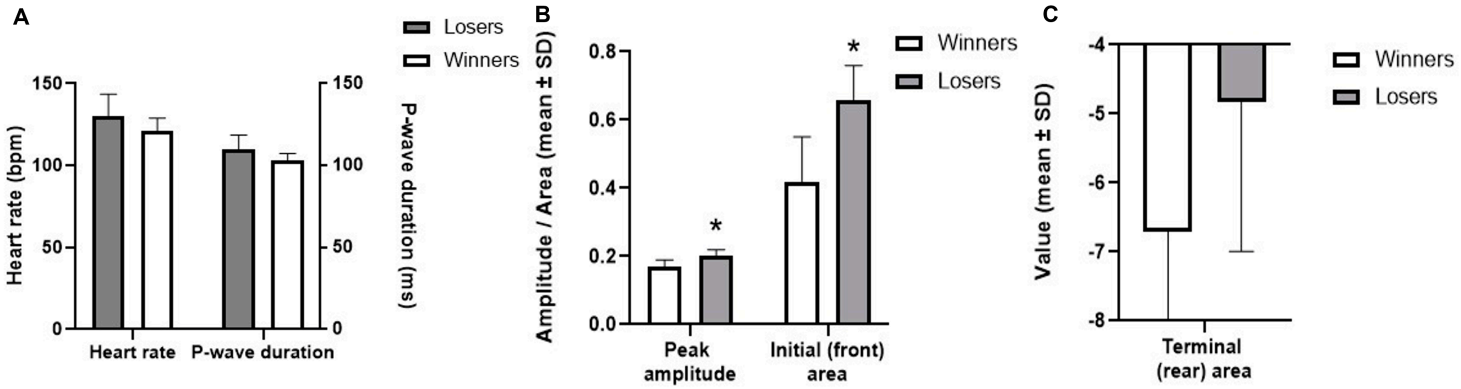


Figure 3

P-wave characteristics during simulated doubles match play. (A) Comparison of heart rate and P-wave duration between winners and losers. (B) Comparison of P-wave peak amplitude and initial (front) area between winners and losers. (C) Comparison of P-wave terminal (rear) area between winners and losers. Values are presented as mean ± SD. *$p < 0.05$ versus losers.