

Research article

Using Inertial Measurement Units to Quantify External Load in Men's Singles Badminton Matches: Insights from Set Outcomes and Score Gaps

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Abstract

Quantifying external load using kinematic variables from inertial devices provides crucial insights into player performance. This study analyzed load variables in men's singles badminton matches, differentiating between set outcomes (winners vs. losers) across different score gaps (0-5, 6-10, >10 points). Data were collected from 18 highly trained players (110 sets) using the Catapult Vector S7 microtechnology units, housed with a 100hz accelerometer, gyroscope and magnetometer. The results indicated that set winners exhibited a lower player load (estimated difference [ED] and 95% CI = -14.1 [-26.20, -1.78], $p = 0.023$), covered less distance (ED = -134.84 [-248.99, -17.01], $p = 0.02$), performed fewer explosive efforts (defined as the sum of high-intensity accelerations, decelerations, and changes of direction [COD]) (ED = -19.75 [-31.85, -7.33], $p = 0.002$), CODs (ED = -21.02 [-34.18, -7.67], $p = 0.003$), and accelerations (ED = -7.03 [-13.16, -0.73], $p = 0.03$) than set losers. Notably, when the score gap was narrow (0-5 points), set winners performed more explosive efforts and CODs than set losers (adjusted $p = 0.0412$ and 0.0499 , respectively). However, as the score gap widened (6-10 and >10 points), set winners exhibited fewer explosive efforts and CODs (all adjusted $p < 0.05$). Furthermore, when the score gap exceeded 10 points, set winners demonstrated a lower player load, covered less distance, and performed fewer right-side CODs (all adjusted $p < 0.05$). These findings suggest that winners generally have a lower external load in men's singles badminton matches. However, when opponents are evenly matched, on-court movement may play a pivotal role in determining the outcome.

Key words: Badminton; external load; inertial measurement units; racket sports; performance.

Introduction

Badminton is a racquet sport characterized by its high-intensity and intermittent nature, demanding high-level physical conditioning, technical proficiency, and tactical acumen from players (Phomsoupha and Laffaye, 2015). Understanding the external load in badminton matches is essential for optimizing training programs, preventing injuries, and enhancing performance. External load is defined as the measurable physical outputs imposed on the athlete (e.g., displacement/speed, acceleration-deceleration events, sprint and change-of-direction [COD] counts)

(Impellizzeri et al., 2019). Despite its significance, research on external load in badminton remains limited, particularly in comparison to other racket sports such as tennis and padel (Miralles et al., 2025; Perri et al., 2023). Unlike tennis, which emphasizes prolonged rallies involving continuous movement and greater total distance due to larger courts, badminton's smaller playing area and short-duration, high-intensity movements result in an external load profile characterized by explosive efforts and frequent COD. However, most studies have concentrated on notational analysis for technical statistics and temporal structure, with limited attention paid to external load metrics such as explosive efforts, COD, and covered distance (Abdullahi et al., 2019; Santiano et al., 2025; Winata et al., 2025).

Monitoring external load in badminton has historically been constrained by technical limitations, particularly the inability of video-based systems to deliver real-time data. While these systems have been validated for notational analysis in badminton, offering reliable data into temporal and technical metrics (Abdullahi et al., 2019), they fall short in delivering immediate feedback. Recent advances in inertial measurement unit (IMU) technology now allow real-time assessment of key external load metrics (García-López et al., 2025), including the number of CODs, accelerations, decelerations, jumps, covered distance, and player load (Abdullahi et al., 2019; Mackay et al., 2025). Among these, player load is a valid and reliable metric derived from accelerometry, and it has become a widely adopted performance monitoring tool across team and racket sports (Hollville et al., 2021). In badminton, several studies have employed IMUs to analyze external load. However, most studies have focused on the effects of IMU placement on player load measurement, and few have comprehensively reported external load indicators such as the number of CODs, accelerations, decelerations, jumps, and covered distance (Chen et al., 2022; Fu et al., 2021; García-López et al., 2025; Liu et al., 2024). Although these methodological studies establish a foundation for accurate load measurement, they do not extend to comparative analyses of performance outcomes, as seen in other racket sports (e.g., winner-loser differences in padel) (Miralles et al., 2025; Tena et al., 2023).

Analyzing external load in relation to set outcomes provides valuable insights into player performance (such as movement efficiency, intensity of efforts, and overall workload) that differentiate winning from losing players, as evidenced in other racket sports, where winners and losers exhibit significant differences in external load metrics. For example, in squash, winners cover less distance than losers. This happens because of better anticipation and tactical efficiency. It forces opponents into harder positions (Vučkovic and James, 2010). In paddle, winners show higher mobility than losers. They cover more distance and do more accelerations per hour. This means higher movement and acceleration rates are advantageous (Miralles et al., 2025). The disparity in scores during a match reflects the skill differential between players. Narrow score gaps may necessitate increased intensity, such as more explosive efforts and changes of direction, to resolve ties in closely contested matches. Conversely, larger score gaps may allow the leading player to conserve energy through efficient play. Investigating how external load varies with match outcomes and points differentials in badminton is both valuable and novel. Such research can identify sport-specific strategies, such as enhancing explosive actions in tightly contested sets or emphasizing efficiency in less challenging ones.

In badminton, while previous studies have explored differences based on sex and discipline (e.g., singles vs. doubles) in external mechanical work (Santiano et al., 2025), the effects of match outcomes and score gaps on external load remain unknown. Therefore, the primary objective of this study was to utilize wearable IMU technology to quantify external load in men's singles badminton matches. The secondary objective was to examine differences in external metrics across set outcomes (winners vs. losers) and score gaps (0-5, 6-10, >10 points). Based on evidence indicating substantial differences in external load between winners and losers in other racket sports, and how these differences are influenced by the match context (Miralles et al., 2025; Vučkovic and James, 2010), and considering that in badminton matches, winners may use techniques and tactics to make opponents run more, thereby winning the game, we therefore propose the hypothesis that set winners generally exhibit a lower external load compared to losers, although this disparity may vary with the score gap.

Methods

Participants

An a priori power analysis using G*Power software (Version 3.1; Universität Düsseldorf, Germany) for repeated measures ANOVA indicated that a sample size of 16 was required to detect an effect size ($f = 1.00$) with $\alpha = 0.05$ and power = 0.80, assuming 2 groups, 3 measurements (score gap categories) (García-López et al., 2025). A total of 18 “highly trained/national level” (Tier 3 (McKay et al., 2022)) male badminton players, aged between 19 and 24 years, were included in the study. Participants were classified as Tier 3 based on their regular participation in national-level competitions and structured training programs. They trained 5 days per week for 2-3 hours per session, including technical drills, physical conditioning (e.g.,

strength, agility, and endurance), and match simulations (McKay et al., 2022). Seventeen players were right-handed, and one was left-handed with a mean $\pm$ SD of age (22.33 ± 1.78 years), height (1.78 ± 0.05 m), body weight (71.44 ± 6.24 kg) and training experiences (11.39 ± 2.33 years). To ensure consistency in directional analysis, the movement data of the left-handed player were mirrored. The study was approved by the Beijing Sport University Research Ethics Committee (Ref: 2025220H) and conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent prior to participation.

Instrument

External load data were collected using the Catapult™ Vector S7 (Catapult Sports, Melbourne, Australia), a wearable microtechnology device that integrated an accelerometer, gyroscope, and magnetometer. The device has demonstrated high validity and reliability in capturing movement characteristics in indoor court-based sports (Mackay et al., 2025). Prior to each match, a standardized calibration procedure was conducted for each IMU in accordance with the manufacturer's guidelines. The device was securely positioned in a custom-made vest or pouch on the upper back, between the scapulae, near the C7-T1 vertebrae. This location is commonly used in sports monitoring and has been shown to be effective for capturing whole-body movements (Liu et al., 2024). Throughout the matches, the Catapult™ Vector S7 device recorded key external load variables at a frequency of 100 Hz, which real-time monitoring via Openfield Software (v3.4.0, Catapult Sports, Melbourne, Australia) to ensure precise data capture.

Experimental procedure

Eighteen participants were randomly assigned to play singles matches on standard indoor badminton courts (Victor C-7051G, Nanjing, China). Matches were scheduled using an adaptive pairing method based on prior performance to ensure balanced and diverse matchups, following a format inspired by the Swiss draw tournament system (Sziklai et al., 2022). Each match consisted of two sets played using the official 21-point rally scoring system (Treating each set as an independent unit of observation). Prior to the general warm-up, players donned a vest without the inertial device. The device was inserted into the vest after players completed specific warm-up exercises and was activated three minutes before the match, capturing data from the first serve to the end of the match.

Variables

The following external load metrics were derived from the IMU data using proprietary algorithms in the Openfield software (García-López et al., 2025):

Player load: A vector magnitude derived from accelerometer data, measured in arbitrary units (au). It is calculated by taking the square root of the sum of squared rates of change in acceleration across three axes, divided by a scaling factor of 100 (Boyd et al., 2011).

Explosive Efforts: The sum of high-intensity accelerations, decelerations, and changes of direction (both left

and right). “High-intensity” was defined using manufacturer default thresholds: above 3m/s (Mackay et al., 2025).

COD Count: Total number of changes of direction (left and right combined). A COD was detected as an abrupt change in movement direction exceeding 45° within a 0.2-second window, based on integrated accelerometer and gyroscope data, with left-side CODs at angles from -135° to -45° and right-side CODs at 45° to 135° (Mackay et al., 2025).

Forward Movements: Number of movements occurring at angles between -45° and 45°.

Backward Movements: Number of movements with angles between ±135° and 180°.

Left-side COD Count: Number of changes of direction at angles from -135° to -45°.

Right-side COD Count: Number of changes of direction at angles from 45° to 135°.

Acceleration Count: Total number of accelerations exceeding 2 m/s².

Decelerations Count: Total number of decelerations below -2 m/s².

Total jump Count: Number of jumps recorded during the match.

Covered Distance (m): Total distance covered during match play, estimated from integrated accelerometer data and often refined using proprietary algorithms within the IMU software (García-López et al., 2025).

Data processing

Raw data from the IMUs were downloaded post-match using Openfield software. The software applied proprietary filters and algorithms to calculate the external load metrics for each set played by each participant. Match scores were manually recorded by official referees. To protect participant privacy, the federation anonymized the data before transferring it to the researchers for analysis. For analysis purposes, each set was treated as an individual unit of observation. The “winner” and “loser” of each set were identified. Sets were then categorized based on the final score gap between the winner and loser: close gap (0-5 points difference; e.g., 21-19, 23-21, 21-16), moderate gap (6-10 points difference; e.g., 21-15, 21-11) and large gap (>10 points difference; e.g., 21-10, 21-9). Data were averaged per set for each player under each condition (winner/loser and score gap category).

Data analysis

Data analysis was performed using RStudio (RStudio, PBC, Boston, MA, USA). Descriptive statistics (Mean ±

SD) were calculated for all external load metrics. Data normality was assessed using the Shapiro-Wilk tests. Linear mixed-effects models were employed to compare external load metrics between winners and losers (set outcomes) within each score gap category (0-5, 6-10, and >10 points). Set outcomes, score gaps, and their interaction were treated as fixed effects, while participant ID was included as a nested random effect. Pairwise comparisons between win and lose outcomes across different score gap categories were conducted, with p-values adjusted using the false discovery rate (FDR) method to control type I error and maintain statistical power. Estimated differences (ED), estimated marginal means (EMM) with 95% confidence intervals (CI), and Cohen’s d effect sizes (ES) with corresponding 95% CI and percentage differences with standard error (SE) for key comparisons were calculated. Statistical significance was set at $p < 0.05$.

Results

A total of 110 sets from 55 matches were included in the analysis. The distribution of sets across the score gap categories was as follow: 40 sets in the 0-5 point gap, 38 sets in the 6-10 point gap, and 32 sets in the >10 point gap. Descriptive statistics for all external load metrics for winners, losers and overall are summarized in Table 1.

Effect of set outcome and score gap

Table 1 presents the main effects of set outcome and score gap on external load metrics. Compared to losers, winners exhibited significantly lower player load (ED = -14.1 [-26.20, -1.78]; ES = -0.96 [-1.78, -0.13], -4.79 ± 5.21%, $p = 0.023$), fewer explosive efforts (ED = -19.75 [-31.85, -7.33]; ES = -1.32 [-2.16, -0.49], -9.58 ± 5.22%, $p = 0.002$), total CODs (ED = -21.02 [-34.18, -7.67]; ES = -1.41, [-2.32, -0.50], -9.00 ± 5.70%, $p = 0.003$), including both left-side (ED = -12.10 [-22.83, -1.29]; ES = -0.94 [-1.81, -0.08], -9.26 ± 4.60%, $p = 0.03$) and right-side (ED = -10.26 [-16.13, -4.39]; ES = -1.48 [-2.36, -0.61], -14.74 ± 2.50%, $p = 0.001$) directions, accelerations (ED = -7.03 [-13.16, -0.73]; ES = -0.95 [-1.80, -0.10], -11.69 ± 2.62%, $p = 0.03$) and covered distance (ED = -134.84 [-248.99, -17.01]; ES = -0.96 [-1.78, -0.13], -4.78 ± 49.48%, $p = 0.02$). However, no significant differences were observed between winners and losers for forward and backward movement counts ($p = 0.06$), decelerations ($p = 0.06$), and total jumps ($p = 0.84$). Compared to sets with a score gap of >10, no significant main effects were found for score gap of 0-5 or 6-10 points on external load metrics (all $p > 0.05$; see Table 2).

Table 1. External load metrics (Mean ± SD) per set between winners and losers.

Metric	Overall	Winner	Loser
Player Load (au)	74.06 ± 19.14	73.95 ± 20.70	74.18 ± 17.64
Explosive Efforts	55.85 ± 20.26	55.56 ± 22.98	56.13 ± 17.33
COD Count	62.35 ± 22.25	61.65 ± 25.29	63.04 ± 18.94
Forward Movements Count	12.83 ± 6.50	13.55 ± 6.45	12.11 ± 6.52
Backward Movements Count	9.88 ± 7.33	9.76 ± 6.70	10.00 ± 7.98
Left-side COD Count	45.77 ± 24.07	47.67 ± 24.21	43.87 ± 24.01
Right-side COD Count	16.57 ± 20.33	13.98 ± 17.37	19.16 ± 22.78
Acceleration Count	22.64 ± 10.94	23.82 ± 10.94	21.45 ± 10.92
Deceleration Count	15.44 ± 9.39	15.49 ± 8.74	15.38 ± 10.08
Total jump Count	21.58 ± 9.64	22.96 ± 10.37	20.20 ± 8.73
Covered Distance (m)	703.60 ± 181.85	702.51 ± 196.65	704.69 ± 167.55

Table 2. The main effects of set outcome and score gap on external load, and the linear mixed model statistics. Values reported are EMM and ES with 95% CI. Negative estimated differences for match indicate values were lower in winners compared to losers, for score gap they indicate values were lower in 0-5 and 6-10 compared to >10.

	Factors										Model statistics			
	Set outcomes		Score gap				Set outcome * Score gap							
	Estimated Difference (win)	ES	Estimated Difference (0-5)	ES	Estimated Difference (6-10)	ES	Estimated Difference (win*0-5)	ES	Estimated Difference (win*6-10)	ES	ICC	R ² Marginal	R ² Conditional	AIC
Player Load (au)	-14.19 (-26.20 to -1.78)	-0.96 (-1.78 to -0.13)	8.05 (-2.54 to 18.95)	0.54 (-0.19 to 1.28)	-1.11 (-12.01 to 9.86)	-0.07 (-0.8 to 0.6)	21.68 (5.19 to 37.52)	1.46 (0.37 to 2.55)	8.34 (-7.15 to 23.67)	0.56 (-0.51 to 1.63)	0.34	0.22	0.49	911
Explosive Efforts	-19.75 (-31.85 to -7.33)	-1.32 (-2.16 to -0.49)	2.92 (-7.74 to 13.76)	0.20 (-0.54 to 0.93)	1.47 (-9.55 to 12.6)	0.10 (-0.66 to 0.86)	31.75 (15.72 to 47.54)	2.13 (1.04 to 3.22)	7.82 (-7.80 to 23.32)	0.52 (-0.55 to 1.60)	0.38	0.25	0.53	915
COD Count	-21.02 (-34.18 to -7.67)	-1.41 (-2.32 to -0.50)	0.67 (-10.98 to 12.42)	0.04 (-0.76 to 0.85)	0.34 (-11.73 to 12.51)	0.02 (-0.81 to 0.86)	33.69 (16.30 to 50.95)	2.26 (1.06 to 3.4)	8.38 (-11.73 to 12.51)	0.56 (-0.61 to 1.74)	0.40	0.21	0.53	934
Forward Movements	-3.88 (-7.83 to 0.14)	-0.80 (-1.6 to 0.04)	1.68 (-1.81 to 5.17)	0.35 (-0.40 to 1.09)	2.96 (-0.69 to 6.57)	0.61 (-0.16 to 1.38)	6.85 (1.62 to 12.02)	1.42 (0.31 to 2.52)	1.94 (-3.15 to 7.02)	0.40 (-0.68 to 1.48)	0.44	0.14	0.51	683
Backward Movements	-3.76 (-7.59 to 0.16)	-0.82 (-1.67 to 0.04)	1.52 (-1.87 to 4.99)	0.33 (-0.42 to 1.08)	-2.66 (-6.16 to 0.85)	-0.58 (-1.36 to 0.21)	4.46 (-0.74 to 9.50)	0.97 (-0.15 to 2.08)	2.46 (-2.50 to 7.36)	0.53 (-0.56 to 1.63)	0.56	0.12	0.61	680
Left-side COD Count	-12.10 (-22.83 to -1.29)	-0.94 (-1.81 to -0.08)	1.66 (-7.83 to 11.19)	0.13 (-0.63 to 0.89)	2.99 (-6.89 to 12.9)	0.23 (-0.56 to 1.03)	19.54 (5.48 to 33.58)	1.52 (0.39 to 2.65)	1.22 (-12.63 to 15.06)	0.10 (-1.01 to 1.21)	0.69	0.08	0.72	902
Right-side COD Count	-10.26 (-16.13 to -4.39)	-1.48 (-2.36 to -0.61)	-1.75 (-6.94 to 3.44)	-0.25 (-1.03 to 0.52)	-3.31 (-8.73 to 2.09)	-0.48 (-1.28 to 0.33)	15.17 (7.50 to 22.82)	2.19 (1.05 to 3.33)	7.22 (-0.34 to 14.78)	1.04 (-0.08 to 2.17)	0.85	0.06	0.86	788
Accelerations	-7.03 (-13.16 to -0.73)	-0.95 (-1.80 to -0.10)	3.69 (-1.69 to 9.12)	0.50 (-0.25 to 1.2)	4.95 (-0.65 to 10.55)	0.67 (-0.11 to 1.40)	9.99 (1.81 to 18.00)	1.35 (0.24 to 2.50)	2.01 (-5.90 to 9.84)	0.27 (-0.83 to 1.40)	0.55	0.14	0.61	777
Decelerations	-4.90 (-9.89 to 0.22)	-0.82 (-1.67 to 0.03)	1.47 (-2.9 to 5.98)	0.24 (-0.51 to 1.00)	-3.66 (-8.19 to 0.91)	-0.61 (-1.39 to 0.17)	6.42 (-0.37 to 12.97)	1.07 (-0.04 to 2.19)	3.18 (-3.27 to 9.54)	0.53 (-0.57 to 1.63)	0.55	0.12	0.60	734
Total jumps	-0.67 (-6.99 to 5.88)	-0.09 (-0.91 to 0.74)	3.95 (-1.60 to 9.67)	0.51 (-0.22 to 1.24)	0.40 (-5.31 to 6.19)	0.05 (-0.70 to 0.81)	4.98 (-3.54 to 13.2)	0.64 (-0.44 to 1.72)	0.19 (-8.00 to 8.23)	0.02 (-1.04 to 1.09)	0.32	0.11	0.39	776
Covered Distance (m)	-134.84 (-248.99 to -17.01)	-0.96 (-1.78 to -0.13)	76.33 (-24.38 to 179.80)	0.54 (-0.19 to 1.27)	-10.87 (-114.3 to 93.37)	-0.08 (-0.84 to 0.68)	206.1 (49.4 to 356.6)	1.46 (0.38 to 2.55)	79.44 (-67.7 to 225.1)	0.56 (-0.50 to 1.63)	0.34	0.22	0.49	1380

Note: Bold denotes statistically significant ($p < 0.05$). ICC = Intraclass Coefficient. AIC = Akaike Information Criterion. Negative ED indicates lower values in winners/0-5/6-10 groups.

Effects of the interaction between set outcome and score gap

Significant interaction effects were observed between set outcome (winners) and a score gap of 0-5 points on player load (ED = 21.68 [5.19, 37.52]; ES = 1.46 [0.37, 2.55], $p = 0.008$), explosive efforts (ED = 31.75 [15.72, 47.54]; ES = 2.13 [1.04, 3.22], $p = 0.0002$), COD count (ED = 33.69 [16.30 to 50.95]; ES = 2.26 [1.06, 3.40], $p = 0.0003$), forward movements (ED = 6.85 [1.62, 12.02]; ES = 1.42 [0.31, 2.52], $p = 0.01$), left-side COD (ED = 19.54 [5.48, 33.58]; ES = 1.52 [0.39, 2.65], $p = 0.009$), right-side COD (ED = 15.17 [7.50, 22.82]; ES = 2.19 [1.05, 3.33], $p = 0.0003$), accelerations (ED = 9.99 [1.84, 18.00]; ES = 1.35 [0.24, 2.50], $p = 0.02$), and covered distance (ED = 206.10 [49.42, 356.58]; ES = 1.46 [0.38, 2.55], $p = 0.009$). In contrast, no significant interaction effects were found

between winners and the 6-10 score gap on any external load metric (all $p > 0.05$; see Table 2).

Pairwise comparisons for winners and losers of different score gap

Figure 1 illustrates the results of pairwise comparisons between winners and losers across different score gap categories. Winners in the 0-5 point score gap exhibited significantly higher values than losers in explosive efforts ($20.56 \pm 5.22\%$, adjusted $p = 0.0412$) and COD counts ($19.53 \pm 5.70\%$, adjusted $p = 0.0499$). Conversely, winners in the 6-10 point score gap consistently exhibited lower values in explosive efforts ($-20.96 \pm 5.34\%$, adjusted $p = 0.0412$) and COD count ($-19.57 \pm 5.82\%$, adjusted $p = 0.0499$).

Similarly, in the >10 score gap, winners demonstrated significantly lower values in player load ($-19.81 \pm 6.34\%$, adjusted $p = 0.0487$), explosive efforts ($-35.62 \pm 6.36\%$, adjusted $p = 0.0072$), COD count ($-32.73 \pm 6.89\%$, adjusted $p = 0.0093$), right-side COD ($-63.47 \pm 3.05\%$, adjusted $p =$

0.0058), and covered distance ($-19.82 \pm 60.19\%$, adjusted $p = 0.0490$) compared to losers. Furthermore, no significant differences were observed in forward movements, left-side COD, and accelerations across all score gap categories (all adjusted $p > 0.05$).

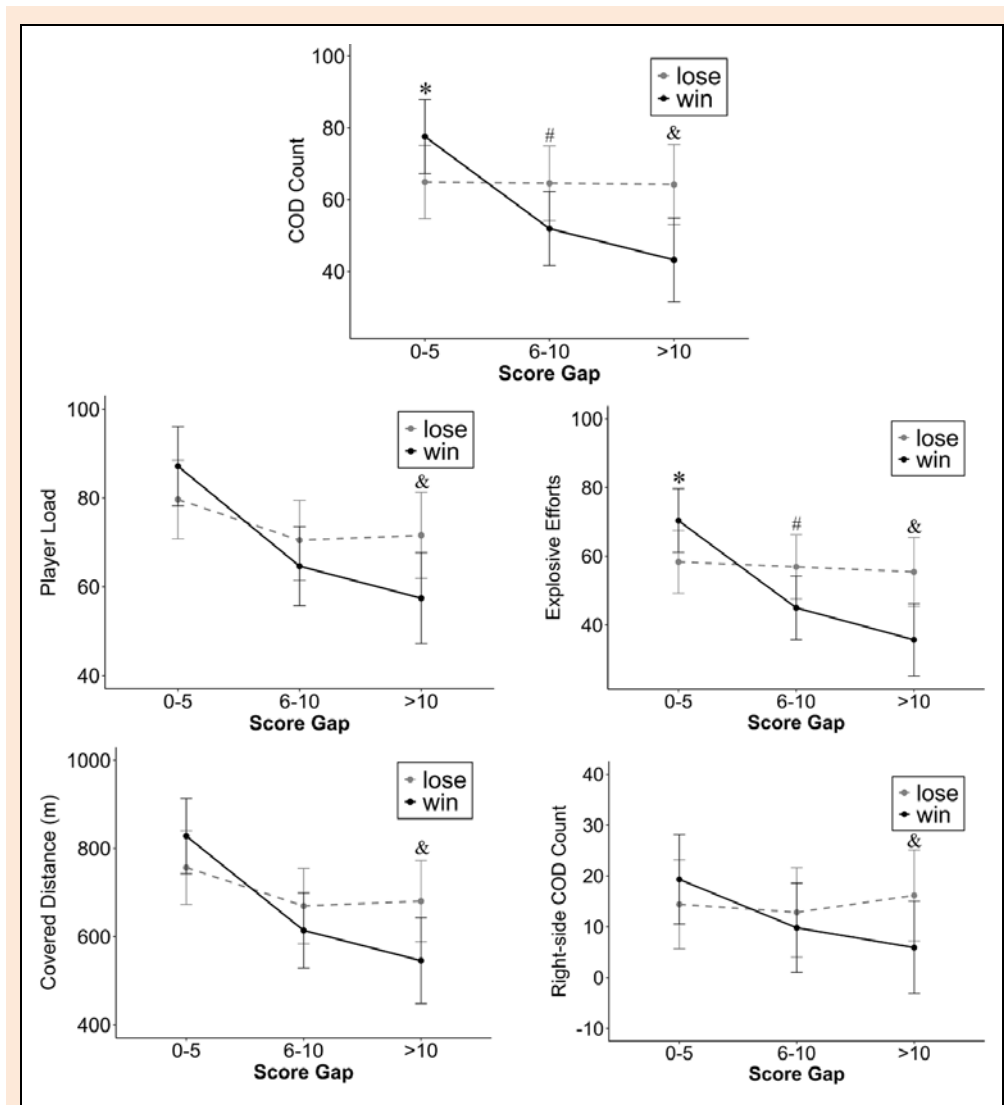


Figure 1. Pairwise comparisons of load variables between winners and losers across different score gap categories (0–5, 6–10, >10 points). Data presented as Estimated Marginal Means ± 95% Confidence Intervals. *Adjusted $p < 0.05$ between winners and losers under 0–5 score gap; # Adjusted $p < 0.05$ between winners and losers under 6–10 score gap; & Adjusted $p < 0.05$ between winners and losers under >10 score gap.

Discussion

This study analyzed external load variables in men's singles badminton matches, differentiating between set outcomes (winners vs. losers) and score gap (0–5, 6–10, and >10 points). Overall, winners exhibited lower external loads than losers in player load, explosive efforts, COD counts, accelerations, and covered distance. Notably, in narrow score gaps (0–5 points), winners performed more explosive efforts and CODs than losers, whereas in wider gaps (6–10 and >10 points), winners showed fewer of these metrics. Additionally, in > 10-point gaps, winners had lower player load, distance, and right-side CODs. These findings verified our hypothesis that winners would exhibit lower

external loads than losers, though differences varied by score gap, with winners showing higher explosive efforts in narrow gap sets. Thus, in men's singles badminton, winners tend to control their opponents using tactics and techniques, leading to lower external loads overall, but in closely match, on-court movement may play a pivotal role in determining the outcome.

A mean Player Load of 74.06 au per set reflects substantial whole-body exertion, consistent with Santiano et al. (2025) using markerless motion analysis in competitive badminton matches involving singles and doubles across sexes, reported player load values ranging from 67.1 to 94.9 AU per point, with higher loads in males than females but similar across disciplines. The high frequency of explo-

sive efforts (mean = 55.85) and total jumps (mean = 21.58) underscore the sport's dynamic and powerful movements, such as lunges and smashes (Smith et al., 2023). Despite potential accuracy limitations associated with IMU-based distance estimation indoor settings (Al-Amri et al., 2018; Mackay et al., 2025), players covered an average distance of 703.6 m per set, which is noteworthy given the small playing area. However, as all measurements were taken under identical indoor conditions using the same devices, these limitations are unlikely to have biased the comparative results between winners and losers. Players performed an average of 62.35 CODs per set, with a noticeable dominance on left-side (mean = 45.77) compared to the right side (mean = 16.57). This imbalance may be influenced by opponents' strategic targeting of the backhand side. The high frequency of CODs, combined with repeated high-intensity accelerations (22.64 per set) and decelerations (15.44 per set), highlights that badminton is characterized by a movement profile dominated by rapid directional changes. These metrics offer more precise insights into mechanical stress compared to global indicators such as Player Load or covered distance (Mamon Jr et al., 2022). The use of IMUs in live match settings enables ecologically valid assessments (Iosa et al., 2016; Picerno et al., 2021), facilitating the development of training programs tailored to match-specific demands (Edel et al., 2023) and supporting load management strategies to mitigate the risk of non-contact injuries (Fields et al., 2021).

The observation that winners often exhibit lower external loads aligns with the notion that superior technical skills, tactical intelligence, and movement efficiency contribute to competitive success (Shan, 2024). Winners are likely more proficient at anticipating opponents' actions, controlling the pace of play, and executing precise shots. These abilities can force opponents into more physically demanding situations or provoke errors, thereby reducing the winners' need for extensive movement or high-intensity actions (Alcock and Cable, 2009). Such proficiency may result in fewer overall movements and reduce reliance on metabolically costly explosive efforts, particularly when players hold a clear advantage.

A key finding is the significant interaction between set outcome and score gap, particularly in the 0-5 point category, where winners exhibited more explosive efforts and COD counts than losers. In evenly matched sets, winners appear to escalate efforts via explosive movements and aggressive tactics to gain advantages over similar opponents (Alvarez-Dacal et al., 2025; Valldecabres et al., 2020). Alternatively, they may use offensive strategies to force opponents into lower contact points, necessitating greater court coverage and directional changes (Gómez et al., 2020; Zhang et al., 2013). In contrast, losers fail to match this intensity or fatigue sooner (Abdullahi et al., 2019). In larger gaps (6-10 and >10 points), the pattern reversed, with winners showing lower explosive efforts and COD counts. These findings indicate context-dependent: efficiency in dominant sets versus high-intensity exertion in close ones (Valldecabres et al., 2020). Although interaction effects were significant for forward movements, left-side COD, and accelerations in the 0-5 gap, pairwise comparisons showed no differences. This apparent discrepancy

may occur because a significant interaction indicates a noticeable overall difference in these metrics' response patterns between match outcomes and score gaps, often due to complex, non-parallel trends. Meanwhile, FDR-corrected pairwise comparisons remain non-significant because they lack the power to detect the smaller, specific mean differences in each individual condition after stringent multiple-testing correction. Notably, in the >10 point score gap, winners demonstrated significantly lower right-side COD counts, further supporting the notion of enhanced movement efficiency during more one-sided matches (Sheng et al., 2025).

When winners secured sets with score gaps of 6-10 and >10 points, their external load metrics were significantly lower than those of losers. Several explanations are possible, including increased opponent errors under scoreboard pressure (Buszard et al., 2017), a shift toward more conservative strategies by the leading player (Valldecabres et al., 2020), or superior technical and tactical control enabling the winner to exert less physical effort (Sheng et al., 2025). Conversely, the lack of significant main effects for score gap across all metrics suggests that players may maintain a relatively stable baseline of movement intensity and workload per rally, irrespective of score margin (Santiano et al., 2025). Instead, the interaction between score gap and set outcome appears more influential in determining variations in external load (Valldecabres et al., 2020). No significant differences were observed in forward and backward movements, decelerations, and total jumps between winners and losers. This suggests that these elements may represent fundamental aspects of badminton performance, employed consistently by both groups. Alternatively, limitations of the IMU system and the predefined threshold (e.g., $>2 \text{ m/s}^2$ for decelerations) may have constrained the detection of subtler movement variations that differentiate performance (Mackay et al., 2025).

The comparable number of total jumps between winners and losers suggests that key actions, such as jump smashes, are employed similarly regardless of set outcome, likely reflecting offensive intentions rather than reactive movements (Ramasamy et al., 2025). Likewise, the similarity in deceleration counts may reflect the shared necessity of shot retrieval, regardless of rally control. These findings align with previous research suggesting that lower external loads in winners may reflect superior movement efficiency, a performance characteristic observed in other individual sports (Navas et al., 2020; Vučković and James, 2010). However, this contrasts with findings from team sports like soccer, where winning team often cover greater total distances and perform more high-intensity running, attributable to maintaining ball possession, implementing high-pressing strategies, and executing rapid transitions (Akenhead and Nassis, 2016; Chmura et al., 2018). In contrast, badminton success hinges on rapid multi-directional footwork, frequent short-distance changes of direction, explosive jumps, and precise racket skills, emphasizing movement efficiency and tactical execution rather than sustained high-speed running. These differences underscore the sport-specific nature of physical performance demands, emphasizing that in racket sports like badminton, technical precision, strategic execution, and movement

efficiency are prioritized to minimize energy expenditure and maximize opponent disruption, in contrast to the emphasis on extensive locomotor activity in field-based team sports.

The use of IMUs to quantify player load and movement patterns in court-based sports has become increasingly prevalent (Al-Amri et al., 2018; Iosa et al., 2016; Picerno et al., 2021). Studies in other racket sports, such as tennis, have similarly employed IMUs to analyze specific movements and overall external load (Rigozzi et al., 2023). Although direct comparisons of absolute values are challenging due to variations in sensor technology, data processing algorithms, player levels, and sport-specific demands, our findings regarding the intermittent high-intensity nature of badminton are broadly consistent with existing knowledge of modern racket sports (Cádiz Gallardo et al., 2023). By quantifying CODs and explosive efforts, this study complements prior badminton research, which has predominantly focused on physiological responses, such as heart rate (Alcock and Cable, 2009) or biomechanical analysis of specific strokes and movements, including lunges (Lam et al., 2017) and landings (Kaldau et al., 2022; Wen et al., 2025) by offering a whole-match perspective on locomotor and inertial loads. The finding that winners in closely contested matches exhibit higher physical output represents a novel contribution that warrants further investigation in badminton and other net or court-based sports.

This study is subject to several limitations. First, the sample was limited to highly trained male singles players, which restricts the generalizability of the findings to female athletes, other competition formats, or different skill levels. Second, only a single IMU placed on the upper back was used, which may not fully capture segmental loading, particularly in the upper and lower limbs. Future studies could use multiple IMUs on key body segments (wrists, ankles, lower back) to better capture upper- and lower-limb loading. Finally, the inclusion of internal load metrics (e.g., heart rate) and technical-tactical data (e.g., hitting load) would have provided a more comprehensive understanding of the physical demands encountered during play.

Practical application

The findings of this study present specific, actionable insights for coaches, players, and sport scientists in men's singles badminton. To replicate match demands, coaches can incorporate multi-shuttle drills where a feeder rapidly delivers shuttles to various court corners, requiring players to execute 50-60 changes of direction (CODs) per session, mirroring the average 62 CODs per set observed. In preparation for closely contested sets (0-5 point gaps), implement high-intensity interval training circuits that combine 20-30 seconds of all-out COD shuttles with 10-15 seconds of rest, repeated for 10-15 rounds, to build sustained mobility, as winners in such scenarios demonstrated higher explosive efforts and CODs. To enhance movement efficiency in dominant sets, focus on tactical drills like controlled rally simulations that emphasize shot placement to force opponent movement, thereby reducing personal load while maintaining control. For load monitoring, use inertial measurement units (IMUs) positioned on the upper back to track player load in real-time, setting session targets at 70-

80 au to align with match averages and adjusting weekly volumes to remain below 400-500 au to prevent fatigue and injury.

Conclusion

This study confirms that badminton imposes substantial physical demands, with external load varying according to the score gap between winners and losers. Overall, in men's singles badminton, winners generally exhibit lower external load compared to losers. However, when opponents are evenly matched, player mobility appears to play a pivotal role in determining the match outcome.

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Key points

- Winners generally have a lower external load in men's singles badminton matches.
- Winners performed more explosive efforts and CODs than set losers when the score gap was narrow (0–5 points).
- Player mobility may play a pivotal role in determining the outcome when opponents are evenly matched.

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