©Journal of Sports Science and Medicine (2026) **25**, 761-771
http://www.jssm.org DOI: https://doi.org/10.52082/jssm.2026.761

Research article

Game Density Modulates External Load During Small-Sided Games in Elite U17 Soccer Players

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Abstract
Evidence regarding the influence of relative area per player (ApP), and playing position, on locomotor- and mechanical- external load during small-sided games in elite youth soccer players remains limited. This study aimed to examine associations between continuous ApP and external load during training-based small-sided games in elite U17 soccer players, and to explore whether playing position modified these responses. Twenty-two elite U17 soccer players (16.6 ± 0.47 years) were monitored during small-sided games, using mostly formats such as 4v4, 5v5, and 8v8-using observations derived from individual player responses across SSG bouts under three-game-density conditions. External load variables included total distance (TD); high-speed running distance (HSR); sprint distance (SPRINT); number of sprints (NSPRINTS); accelerations (ACC); decelerations (DEC); high metabolic load distance (HMLD); and, maximal-speed exposure (%MSPEED). Linear mixed-effects models were used to examine associations between continuous ApP and each external load variable, while accounting for repeated observations, including players and session-level clustering. Larger ApP values were positively associated with HSR, SPRINT, NSPRINTS, HMLD, and %MSPEED. In contrast, no significant associations were observed between ApP and TD; ACC; or DEC. No significant main effects of playing position or ApP × position interactions were identified. Supplementary player-level effect-size analyses indicated recurring exploratory positional patterns, particularly for high-speed and sprint-related variables. These findings suggest that ApP is a practical programming variable for scaling high-intensity locomotor and metabolically-demanding external load in elite youth soccer, whereas additional task constraints may be required to specifically target acceleration- and deceleration-based demands.

Key words: Relative playing area, training load monitoring, GNSS tracking, youth athletes.

Introduction

Load management in youth football is a key component of long-term player development, as it underpins training adaptation, performance progression, and the mitigation of overload and injury risk (Gabbett, 2016; Malone et al., 2017a). In applied practice, coaches must make daily decisions about how to manipulate training constraints to achieve specific physical and developmental outcomes. Given the substantial inter-individual variability in biological maturation during adolescence, players within the same chronological age category may differ in physical capacity, load tolerance, and their ability to reach and sustain high-speed running. This variability is particularly relevant when interpreting density effects, as available space may interact with individual locomotor capacity to shape exposure to high-speed and sprint activities in U17 players (Lloyd and Oliver, 2012; Buchheit and Laursen, 2013). These age-specific characteristics increase the need for systematic and individualised monitoring of training load, particularly in junior elite categories, where similar overall training volumes compared to earlier developmental stages are accompanied by a marked increase in training intensity and competitive demands (Dudley et al., 2023; Afonso et al., 2025). Examining training load responses within a single age category may therefore reduce the confounding influence of maturity- and age-related differences, which are known to substantially affect external load responses during adolescence (Buchheit et al., 2010; Lloyd and Oliver, 2012).

External load in football is commonly quantified using player-tracking technologies-such as GPS or GNSS systems-which provide information on total distance; high-speed and sprint running; accelerations; and, decelerations (Akenhead and Nassis, 2016; Malone et al., 2017a). In addition, composite indicators such as Player Load or high metabolic load distance (HMLD) have been proposed to capture combined locomotor and mechanical demands (Buchheit et al., 2014; Malone et al., 2017b). Given the substantial variability in duration and format of small-sided games (SSGs), normalising external load-to-time (e.g., m·min-1) is essential to allow meaningful comparisons between training tasks of different volumes, and training and match demands (Owen et al., 2017; Beato et al., 2023). Accordingly, examining external load responses during SSGs may help inform the potential replication of match demands through density manipulation (Owen et al., 2017; Lacome et al., 2018).However, the present study did not directly compare SSG responses with match-play demands, and such comparisons were therefore beyond its scope.

Small-sided games represent a widely used training modality because they integrate physical conditioning and technical and tactical development, within a representative game environment that includes the ball, opponents, and, decision-making under pressure (Clemente, 2016; Bujalance-Moreno et al., 2019). A major advantage of SSGs lies in their high adaptability, because task constraints-such as pitch size, number of players, and game rules-can be manipulated to purposefully alter players’ acute physiological and locomotor responses (Hill-Haas et al., 2011; Clemente et al., 2023). At the same time, changes in SSG configuration also affect the mechanical components of external

Received: 08 March 2026 / Accepted: 17 August 2026 / Published (online): 01 September 2026

load, including the frequency and intensity of accelerations, decelerations, and physical contacts (Gaudino et al., 2014). From a constraints-led perspective, game density modifies the players‘ perception of options available during SSGs. Larger ApP provides more space and longer transition distances, enabling higher running speeds, whereas smaller ApP increases opponent pressure, and may promote more frequent short actions, accelerations, decelerations, and changes of direction. Thus, game density acts as a task constraint shaping emergent locomotor and mechanical load patterns (Riboli et al., 2020).

Among the various task constraints, training load density-most commonly operationalized as relative area per player (ApP)-has emerged as a key determinant of external load during SSGs (Casamichana and Castellano, 2010; Riboli et al., 2022 Clemente et al., 2020). In this context, higher ApP values correspond to lower game density, whereas lower ApP values reflect higher density conditions. ApP combines pitch size and player number into a single variable, thereby improving comparability across different game formats (Owen et al., 2017; Beato et al., 2023). Evidence from elite youth football consistently demonstrates that higher ApP values (i.e., lower density) allow greater space and time for longer running bouts and higher velocities, resulting in increased locomotor demands, particularly for high-speed running and sprinting expressed relative to time (Owen et al., 2017; Beato et al., 2023; Riboli et al., 2023). Conversely, lower ApP values restrict available space, and shift the load profile toward a greater mechanical component, characterised by more frequent accelerations and decelerations (Casamichana et al., 2012; Riboli et al., 2022). Importantly, mechanical indicators appear to show a weaker and less consistent relationship with ApP manipulation than high-speed locomotor metrics, suggesting that density predominantly-though not exclusively-regulates the locomotor component of external load (Gaudino et al., 2014; Riboli et al., 2022).

Playing position represents an additional factor that may influence external load responses, as positional roles are associated with distinct movement patterns and match demands (Vigh-Larsen et al., 2018; Morgans et al., 2024). In adult football, midfielders and forwards are typically exposed to higher locomotor and mechanical loads than central defenders (Di Salvo et al., 2007; Mendez-Villanueva et al., 2013). In youth football, positional differences have also been reported during both match play and SSGs, although findings are less consistent and may be influenced by age, maturity status, and the structured nature of academy training environments (Abbott et al., 2018). Moreover, large inter-individual variability in growth and maturation during adolescence complicates the direct transfer of density thresholds derived from adult samples to younger age categories (Buchheit et al., 2010; Lloyd and Oliver, 2012). Although the thresholds applied in the present study are based on recent research in elite youth populations, their robustness may still vary depending on contextual and population-specific characteristics, including the present Czech U17 cohort. In addition, substantial between-player variability in external load responses-during small-sided games-has been reported-even within homogeneous training groups-highlighting the need to consider individual and position-specific response patterns, rather than relying solely on group mean values (Lacome et al., 2018). Therefore, while ApP is widely used to prescribe SSGs aimed at replicating or exceeding match demands, it remains unclear to what extent playing position modifies external load responses across different density conditions within a single elite youth category. Accordingly, the primary aim of this study was to examine the association between continuous relative area per player (ApP), and external load during small-sided games in elite U17 soccer players, with a secondary aim of exploring whether playing position modified these ApP-related responses. It is hypothesized that lower-density conditions (i.e., higher ApP) would elicit greater locomotor demands, particularly those associated with high-speed running, sprint distance, number of sprints, and relative maximal speed. It is further hypothesized that traditional positional differences would be attenuated in this applied academy context, due to the club’s developmental philosophy involving frequent positional rotation and exposure to multiple playing roles during training.

Methods

Research Design

A repeated-measures, observational, within-season monitoring design was employed to examine associations between relative-area-per-player (ApP), and external load responses during training-based small-sided games, implemented within the regular training process between July and December, 2025. Data were collected under ecologically valid conditions, with all analysed SSGs performed as part of the team’s standard training programme. Data were collected across four training sessions implemented on training days ranging from MD+2 to MD-1, reflecting their integration within the competitive microcycle. Session objectives differed according to the microcycle context: MD+2 was primarily oriented toward controlled game-based exposure, whereas MD-3 and MD-2 included higher-intensity game-based training stimuli, and MD-1 was primarily focused on pre-match tactical activation.

All SSGs were played without the offside rule, and consistently included goalkeepers. This configuration was selected to preserve representative attacking and defensive behaviours, while promoting continuity of play. Across the observation period, the most frequently applied game formats were 4v4, 5v5, and 8v8, which together constituted the core SSG methodology used by the team. No formal touch limitations were applied, and standard scoring rules were used. Coaches provided standardised verbal encouragement to maintain playing intensity and tactical engagement, but no additional running incentives or externally imposed physical targets were used. An adequate number of balls was provided to minimise stoppages, and corner kicks were omitted to maintain the flow of play, with ball possession retained by the attacking team following situations that would normally result in a corner kick. For most SSG formats, the work:rest structure followed an approximately 1:1 ratio, with games typically organised into 3 - 6 repetitions across 1 - 3 series, depending on the intended training stimulus and microcycle context.

The relative area per player (ApP) was treated as the primary independent variable, and calculated as the total pitch area divided by the number of active players participating in each game. Based on ApP values, SSGs were categorised into three density conditions according to the thresholds proposed by de Dios-Álvarez et al.,(2024): high density (ApP < 150 m^2·player-1); medium density (ApP 151 - 250 m^2·player-1); and, low density (ApP ≥ 251 m^2·player-1). A total of 340 individual player observations were included in the final analysis, representing repeated measures across multiple training sessions. Of these, 67 observations were classified as high-density games, 107 as medium-density games, and 166 as low-density games. Observations were distributed across playing positions and training sessions in accordance with the applied training environment and the club's rotational approach to player positioning. All training sessions were supervised by qualified academy coaches to ensure methodological consistency, appropriate intensity, and continuity of physical load.

Participants

Given the applied observational design and the use of linear mixed-effects models (LMM), a priori sample-size calculation was not feasible. Therefore, a sensitivity power analysis was conducted using G*Power (version 3.1.9.7; Heinrich-Heine-Universität Düsseldorf, Germany) (Faul et al., 2007) to estimate the minimum detectable effect size for the primary within-subject factor (game density: low, medium, high). As G*Power does not directly implement mixed-effects modelling procedures, the analysis was approximated using the F-test family (ANOVA: Repeated measures, within factors), reflecting the repeated-measures structure of the density variable. The following parameters were specified: $\alpha = 0.05$; statistical power $(1 - \beta) = 0.80$; number of groups = 1; number of repeated measurements = 3; total sample size = 22; and an assumed correlation among repeated measures of $r = 0.50$. The nonsphericity correction (ε) was set to 1.00 for primary estimation. Under these assumptions, the available sample size ($n = 22$) was sufficient to detect effects of at least medium magnitude (Cohen's $f = 0.28$). According to conventional benchmarks (Cohen, 1988), this corresponds to a medium effect size (small = 0.10, medium = 0.25, large = 0.40). Although a total of 340 individual observations were analysed, inferential power in mixed-effects modelling is primarily determined by the number of independent subjects (clusters), given the hierarchical structure of repeated observations nested within players (McNeish and Stapleton, 2016). The sensitivity analysis, therefore, reflects the effective participant-level sample size rather than the total number of observations. The study was thus adequately powered to detect moderate-to-large main effects of game density. However, smaller effects-particularly those related to playing position or density × position interactions-may have remained undetected. For this reason, standardised effect sizes (Hedges' g) were additionally reported to support practice-oriented interpretation.

The research sample consisted of 22 male players from a Czech elite youth football academy, who were active members of the U17 squad during the 2025/2026 season. As of December 2025, players' mean age was 16.6 ± 0.47 years, with a mean football training experience of 12.1 ± 0.7 years. All participants were engaged in a long-term, systematic training process embedded within the club's structured player development programme. The academy operates under a unified methodological framework that emphasises technically demanding, game-based training, and frequent positional rotation. Accordingly, players are regularly exposed to multiple playing positions as part of their long-term development, reflecting a developmental philosophy prioritising comprehensive player education over early positional specialisation. The training process is supported by an interdisciplinary performance staff, including football coaches, strength and conditioning specialists, sports psychologists, physiotherapists, and medical personnel, ensuring a holistic approach to player development and load management.

For analytical purposes, players were categorised by primary playing position as central defenders, fullbacks, central midfielders, wide midfielders, or forwards. Each player's primary playing position was initially assigned according to the club's coaching staff designation based on the player's usual competitive role during the season. However, given the academy's developmental philosophy involving frequent positional rotation, the positional category used for analysis reflected the role performed during the observed SSG, whenever this differed from the player's primary squad designation. This approach was used to reduce potential misclassification, and to ensure that positional comparisons reflected the actual playing role within each observation. Goalkeepers were excluded from the analysis due to the position-specific nature of their external load profiles. Players presenting acute illness or injury at the time of data collection were excluded. In cases where injury occurred during the observation period, players were temporarily withdrawn and re-included only after receiving medical clearance, and completing at least one full training microcycle. Data from any training session not fully completed by a player due to injury or other acute reasons were excluded from the analysis. The regular training microcycle consisted of four to five on-field team training sessions (90 min each), one to two gym-based sessions, individual development activities, and one 11v11 league or friendly match (90 min). Only data obtained from on-field team training sessions were included in the present study.

Written informed consent was obtained from all players and their legal guardians. The study was approved by the Ethics Committee of the Faculty of Physical Education and Sport, Charles University (approval number: 090/2025), and was conducted in accordance with the Declaration of Helsinki.

Data collection

External physical load was monitored using Catapult S7 global positioning system (GPS) units (Catapult Sports, Melbourne, Australia), operating at a sampling frequency of 18 Hz and equipped with triaxial accelerometers and gyroscopes sampling at 100 Hz. Each device was positioned between the scapulae, in a dedicated pocket of a tight-fitting elastic vest, in accordance with the manufacturer's recommendations. To minimise inter-unit variability, each player was assigned the same device for all monitored training sessions throughout the investigation period.

GPS units were activated at least 15 minutes prior to the start of each training session, to ensure an adequate satellite connection and stable data acquisition. All SSGs were preceded by a standardised warm-up lasting at least 20 minutes, consisting of progressive activation, movement preparation, and injury-prevention exercises. Players were familiar with the monitoring devices, as their use formed part of the club's regular training routine. Following each session, data were downloaded and processed using the manufacturer's proprietary software in accordance with standardised procedures.

External physical load indicators

To comprehensively characterise the external physical demands imposed on players during small-sided games, a range of locomotor and mechanical load indicators was selected for analysis. Locomotor load was quantified using total distance per minute (TD, $m.min^{-1}$), high-speed running distance per minute (HSR $m.min^{-1}$; > 18 $km{\cdot}h^{-1}$), sprint distance per minute (SPRINT, $m.min^{-1}$; > 24 $km{\cdot}h^{-1}$), and the number of sprints performed per minute (NSPRINTS, $n.m^{-1}$). These variables reflect the players' capacity to perform sustained, high-intensity running actions and are particularly sensitive to manipulations of the playing area and available space. The mechanical component of external load was assessed using the number of high-intensity accelerations (ACC, $n.min^{-1}$; $\geq 3\ m{\cdot}s^{-2}$) and decelerations (DEC, $n.min^{-1}$; $\geq 3\ m{\cdot}s^{-2}$) per minute, capturing the rapid changes in speed and direction that typically occur under constrained space conditions. In addition, high metabolic load distance per minute (HMLD, $m{\cdot}min^{-1}$) was included as a composite indicator, integrating high-speed locomotion and intense acceleration-deceleration actions, thereby providing an estimate of the combined energetic and mechanical demands imposed during SSGs. High metabolic load distance per minute (HMLD, $m{\cdot}min^{-1}$) was derived from the Catapult metabolic power model and represented the distance covered when estimated metabolic power exceeded the manufacturer-defined high-metabolic-load threshold. According to Catapult OpenField documentation, the default HMLD threshold is 25.5 $W{\cdot}kg^{-1}$. Therefore, HMLD was interpreted as a vendor-specific composite metric reflecting distance accumulated during high estimated metabolic power activity, incorporating both high-speed running and intense acceleration-deceleration demands. Finally, maximal-speed exposure (%MSPEED, %), expressed as a percentage of each player's individual maximum speed, was used to contextualise high-speed and sprint activities relative to each player's locomotor capacity. Each player's individual maximum speed was determined as the highest speed recorded during the observation period across all available training sessions and matches. This approach allows for a more individualised interpretation of external load responses and reduces bias associated with between-player differences in absolute sprinting ability. All variables were time-normalised (min^{-1}) to enable meaningful comparisons across SSG formats of different durations. Where appropriate, absolute values were also examined to support descriptive interpretation of the overall training load.

Statistical analysis

All statistical analyses were conducted using Python (version 3.14) with the pandas and statsmodels libraries (Seabold and Perktold, 2010). Descriptive data are reported as means, standard deviations, and 95% confidence intervals. Relative changes between high- and low-density conditions were calculated to support practical interpretation of the observed descriptive differences.

Linear mixed-effects models were used to examine the associations between relative area per player (ApP) and each external load variable, while accounting for the repeated-measures and clustered structure of the data. Because ApP is a continuous variable, it was modelled as a continuous fixed-effect predictor rather than only as a categorical density variable. Separate models were fitted for each external load outcome. Each model included ApP, playing position, and the ApP × position interaction as fixed effects. Repeated observations were clustered within players, and training-session dependency was accounted for by including session-level variance components. This modelling approach allowed the analysis to account for repeated player observations, unequal numbers of observations across players and density conditions, and shared contextual influences within training sessions.

Model outputs are reported as fixed-effect estimates (β), 95% confidence intervals, p-values, and variance components. The primary inference was based on the fixed effect of continuous ApP and the ApP × position interaction. Game density categories were retained for descriptive and applied interpretation only. Model assumptions were evaluated through visual inspection of residual distributions, and fitted-versus-residual plots. Convergence status and variance component estimates were inspected for all models. For selected acceleration-based outcomes, session-level variance approached the boundary of the parameter space, indicating minimal session-level clustering for these variables. However, all final models converged successfully. The level of statistical significance was set at $p < 0.05$.

To support practical interpretation of positional differences within density conditions, pairwise standardized effect sizes were calculated using Hedges' g. To avoid inflation of effect-size estimates due to repeated observations, Hedges' g values were calculated from player-level aggregated means, rather than treating individual observations as independent. Effect sizes were interpreted using conventional thresholds: < 0.20 trivial; 0.20 - 0.49 small; 0.50 - 0.79 moderate; and ≥ 0.80 large. These effect-size analyses were considered exploratory and supplementary to the multilevel mixed-effects models.

Results

Descriptive external load characteristics across the different game density conditions are presented in Table 1. Overall, progressive increases from high- to low-density conditions were observed for variables associated with high-intensity locomotor activity, particularly HSR, SPRINT, NSPRINTS, HMLD, and %MSPEED. The largest relative increases between high- and low-density conditions were identified for sprint-related variables, with SPRINT and NSPRINTS demonstrating increases exceeding 300 - 600%. Similarly, substantial increases were observed for HSR and HMLD, indicating progressively greater exposure to high-speed and metabolically demanding actions as relative playing area increased. In contrast, TD, ACC, and DEC demonstrated comparatively smaller relative changes across density conditions, suggesting that game density primarily influenced high-intensity locomotor demands rather than total movement volume or acceleration-based activity.

Results of the multilevel mixed-effects models are presented in Table 2. Significant positive associations between continuous ApP and several external load variables were identified. Specifically, larger relative playing areas were associated with greater HSR (β = 0.036, 95% CI = 0.008 to 0.064, p = 0.013); SPRINT (β = 0.0068, 95% CI = 0.001 to 0.013, p = 0.020); NSPRINTS (β = 0.00048, 95% CI = 0.00009 to 0.00086, p = 0.015); HMLD (β = 0.082, 95% CI = 0.015 to 0.149, p = 0.017); and %MSPEED (β = 0.041, 95% CI = 0.006 to 0.076, p = 0.023). These findings indicate that increasing relative playing area was consistently associated with greater exposure to high-speed, sprint, and metabolically demanding locomotor actions. Conversely, no significant associations between ApP and TD, ACC, or DEC were observed (all p > 0.05), suggesting that increasing relative playing area did not substantially influence total movement volume or acceleration-based external load variables.

No significant main effects of playing position were identified for any of the analyzed external load variables (all p > 0.05). Furthermore, no significant ApP × position interactions were detected across any of the analyzed models, indicating that the observed effects of relative playing area on external load variables were generally consistent across positional roles. Session-level variance components differed between outcome variables, with greater session clustering observed for HMLD, TD, and %MSPEED, whereas ACC and DEC demonstrated minimal session-level variance contribution. All final mixed-effects models converged successfully.

Although no statistically significant ApP × position interactions were identified, supplementary effect-size analyses based on player-level aggregated means revealed several recurring practical positional patterns across density conditions (Supplementary Table S2). In general, attacking positions, particularly ST and W, tended to demonstrate greater high-speed and sprint-related demands than defensive positions, especially in low- and medium-density conditions. Conversely, CB frequently demonstrated lower exposure to sprint-related and metabolic variables, compared with attacking and wide positions. Recurrent practical positional contrasts were particularly evident for HSR, SPRINT, NSPRINTS, HMLD, and %MSPEED. Several positional patterns were repeatedly observed within the same density condition, suggesting consistent practical differences between defensive and attacking positional roles, despite the absence of statistically significant interaction effects in the multilevel models. These findings should therefore be interpreted cautiously-as exploratory practical patterns-rather than evidence of statistically significant positional moderation of ApP effects.

Table 1. External load variables across different game density conditions. Data are means ± SD (95% CI).

Variable	High Density (n = 67)	Medium Density (n = 107)	Low Density (n = 166)	Change High→Low (%)
TD	91.54 ± 12.69 (88.50 to 94.58)	95.17 ± 12.06 (92.88 to 97.45)	89.00 ± 18.84 (86.13 to 91.87)	-2.8%
HSR	7.67 ± 5.85 (6.27 to 9.08)	14.69 ± 10.59 (12.68 to 16.69)	18.95 ± 10.51 (17.36 to 20.55)	147.0%
SPRINT	0.40 ± 0.94 (0.17 to 0.62)	1.47 ± 1.99 (1.09 to 1.84)	3.00 ± 2.38 (2.64 to 3.36)	659.1%
NSPRINTS	0.05 ± 0.09 (0.02 to 0.07)	0.12 ± 0.15 (0.09 to 0.15)	0.19 ± 0.14 (0.17 to 0.21)	315.2%
ACC	0.54 ± 0.42 (0.44 to 0.64)	0.57 ± 0.40 (0.49 to 0.64)	0.44 ± 0.43 (0.38 to 0.51)	-17.7%
DEC	0.56 ± 0.39 (0.47 to 0.65)	0.65 ± 0.45 (0.56 to 0.73)	0.54 ± 0.41 (0.48 to 0.60)	-3.5%
HMLD	38.26 ± 14.60 (34.76 to 41.75)	44.40 ± 14.03 (41.74 to 47.06)	46.45 ± 31.00 (41.74 to 51.17)	21.4%
%MSPEED	69.34 ± 15.79 (65.56 to 73.13)	77.33 ± 12.16 (75.02 to 79.63)	84.19 ± 13.40 (82.15 to 86.23)	21.4%

Table 2. Multilevel mixed-effects models examining associations between continuous ApP and external load variables

Variable	Fixed effect β (ApP)	95% CI	p-value	Position effect p	ApP × Position p	Session variance
TD	-0.0150	-0.062 to 0.031	0.513	> 0.05	> 0.05	176.8
HSR	0.0360	0.008 to 0.064	0.013	> 0.05	> 0.05	53.8
SPRINT	0.0068	0.001 to 0.013	0.020	> 0.05	> 0.05	3.8
NSPRINTS	0.0005	0.0001 to 0.0009	0.015	> 0.05	> 0.05	0.017
ACC	ns	ns	> 0.05	> 0.05	> 0.05	~0
DEC	ns	ns	> 0.05	> 0.05	> 0.05	~0
HMLD	0.0820	0.015 to 0.149	0.017	> 0.05	> 0.05	528.0
%MSPEED	0.0410	0.006 to 0.076	0.023	> 0.05	> 0.05	180.0

Linear mixed-effects models included repeated observations nested within players with additional session-level clustering. ApP was modelled as a continuous predictor. β = fixed-effect estimate for ApP. CI = confidence interval. ns = non-significant.

Discussion

This study examined the association between relative area per player (ApP) and external load responses during training-based SSGs in elite U17 soccer players, with particular attention given to time-normalised locomotor and mechanical indicators, and the potential moderating role of playing position. The main finding was that increasing ApP was positively associated with high-intensity locomotor and metabolically demanding external load variables, including HSR, SPRINT, NSPRINTS, HMLD, and %MSPEED. In contrast, no significant associations were observed between ApP and TD, ACC, or DEC. However, these findings may partly depend on the selected ACC/DEC threshold. Using multiple acceleration/deceleration intensity bands or continuous threshold approaches could provide a more detailed representation of mechanical load, and could also lead to different conclusions. These findings suggest that relative playing area primarily influences high-speed, sprint-related, and metabolically demanding components of external load rather than total movement volume or acceleration- and deceleration-count variables. No significant main effects of playing position or ApP × position interactions were identified, indicating that the association between ApP and external load was broadly consistent across positional roles. Nevertheless, supplementary player-level effect-size analyses revealed several recurring practical positional patterns, which should be interpreted as exploratory, rather than confirmatory, evidence of positional moderation.

The positive associations between ApP and HSR, SPRINT, NSPRINTS, HMLD, and %MSPEED reinforce the importance of available playing space in enabling high-intensity and metabolically demanding locomotor actions during SSGs. Comparable dose-response relationships between pitch size or ApP, and high-speed or sprint-related outcomes, have been repeatedly reported in both youth and adult cohorts (Casamichana and Castellano, 2010; Hodgson et al., 2014). In elite youth players, larger ApP values appear particularly relevant when the training objective is to approximate match-related high-speed demands and increase exposure to sprinting and high maximal-speed actions (Riboli et al., 2020; 2022). These findings are consistent with meta-analytic evidence showing that larger playing areas systematically increase high-speed and sprint distances across SSG formats (Clemente et al., 2023). Collectively, the present results support the view that ApP is a primary macro-constraint for scaling high-intensity locomotor and metabolically demanding external load during representative, game-based training. From a coaching perspective, this macro-constraint can be manipulated through concrete task-design levers, including pitch size, number of players, and complementary rules that influence available space and transition opportunities. Ecologically, increasing ApP expands the action possibilities available to players by creating more space and time to accelerate, sustain longer running bouts, and reach higher peak speeds.

From an applied perspective, these findings support the use of ApP as a practical programming variable for scaling high-intensity locomotor and metabolically demanding external load during SSGs. When the objective is to increase HSR, sprint distance, sprint frequency, HMLD, or maximal-speed exposure, practitioners may consider using larger ApP formats, corresponding to lower-density game configurations. Conversely, when the aim is to limit high-speed and sprint-related exposure while maintaining a representative, ball-involved training environment, smaller ApP formats may be more appropriate-for example during congested microcycles or return-to-train progressions. Density-based programming models have therefore been proposed as a practical framework for regulating locomotor load through space manipulation (Clemente et al., 2019; Sangnier et al., 2019). For example, high-density formats (< 150 m^2·player-1) may be used when the aim is to constrain space and limit sprint exposure. Medium-density formats (151 - 250 m^2·player-1) may support continuous involvement and overall movement volume, and low-density formats (≥ 251 m^2·player-1) may be selected to increase high-speed running and sprint-related exposure. However, these applied recommendations should be interpreted with caution, as the present findings are based on a limited number of training sessions, and contextual factors-such as microcycle day, session objectives, and coaching constraints-were not formally modelled. Therefore, density-based prescriptions should be adapted to the specific training context, including microcycle timing, session objectives, and coaching constraints.

Importantly, even in larger ApP formats, maximal-speed exposure during SSGs may remain lower and more variable than during match play (Dello Iacono et al., 2023), suggesting that additional methods may be needed when maximal-speed development is a central goal. In practice, this may include complementary task constraints, such as rules encouraging depth runs, or longer transition moments, or the integration of supplementary sprint exposures outside SSGs, particularly in elite youth contexts where weekly training may not fully replicate match high-speed and sprint demands across positions, despite substantial training volumes (Kokstejn et al., 2024).

Unlike high-speed and sprint-related variables, TD was not significantly associated with continuous ApP in the mixed-effects models. Descriptively, TD was highest in the medium-density condition, rather than increasing progressively from high- to low-density formats. This pattern suggests that total movement volume may respond differently to space manipulation than high-intensity locomotor variables. Similar non-linear responses have been reported previously, indicating that TD may be maximised under intermediate constraints that promote continuous movement and frequent involvement, rather than in the largest playing areas where actions may become more episodic (Hill-Haas et al., 2008; Casamichana and Castellano, 2010). From a tactical perspective, intermediate density may create a balance between sufficient space for movement and sufficient opponent proximity to maintain frequent ball turnovers, short attacking-defensive transitions, and repeated support movements. This may increase continuous low- to moderate-intensity activity and explain why TD peaked in the middle-density condition, despite high-speed metrics increasing more clearly in lower-density formats. This reinforces the need to interpret TD and high-speed indicators as partially distinct constructs, and to avoid using TD as a proxy for high-intensity exposure when evaluating density manipulations in SSG design (Clemente et al., 2023). Applied programming should therefore align metric selection with the intended stimulus, using TD to describe overall movement volume and HSR, SPRINT, NSPRINTS, and %MSPEED to describe high-intensity locomotor exposure.

In contrast to HMLD, which was positively associated with ApP, the acceleration- and deceleration-count variables were not significantly associated with relative playing area. This distinction suggests that larger ApP values may increase metabolically demanding locomotor activity, while not necessarily increasing the frequency of discrete acceleration and deceleration events. Previous research indicates that mechanical load responses in SSGs are less consistently driven by space availability and may depend more strongly on additional task constraints, such as touch limitations, scoring rules, pressing constraints, tactical behaviours, and emergent interaction patterns (Hodgson et al., 2014; Sarmento et al., 2018). Meta-analytic evidence similarly indicates smaller and more variable pitch-size effects on mechanical metrics compared with locomotor variables (Clemente et al., 2023). Recent match-based analyses using continuous ACC and DEC thresholds further show that mechanical load characteristics are highly intensity-dependent and age-sensitive, with DEC becoming increasingly prominent at higher thresholds and showing weaker coupling with ACC as intensity rises (Vampola et al., 2025). Together, these findings support a practically important interpretation: increasing ApP alone may be useful for increasing high-speed and metabolically demanding locomotor exposure, but may not be sufficient to meaningfully adjust acceleration- and deceleration-based mechanical demands. Practitioners aiming to target neuromuscular demands related to frequent stop-start actions, or rapid changes of direction, may therefore need to combine ApP manipulation with additional constraints specifically designed to elicit such behaviours.

Playing position did not show a significant main effect for any external load variable, and no significant ApP × position interactions were identified. This indicates that the association between relative playing area and external load was broadly consistent across positional roles in the present sample. Nevertheless, supplementary effect-size analyses based on player-level aggregated means suggested several recurring practical positional patterns, particularly for high-speed, sprint-related, metabolic, and maximal-speed variables. In general, attacking and wide positions-especially ST and W-tended to demonstrate greater exposure to high-speed and sprint-related demands than defensive positions, whereas CB frequently showed lower exposure to sprint-related and metabolic variables. This general pattern is consistent with positional analyses in youth soccer reporting greater high-speed and sprint demands for midfielders and attackers during both matches and SSGs (Beenham et al., 2017; Baptista et al., 2019), as well as match-level evidence in elite U17 players demonstrating positional differentiation in high-intensity running (Kokstejn et al., 2024). In applied academy environments, substantial between-player variability related to maturation, physical capacity, playing style, and rotation policies may attenuate fixed positional effects in inferential models. Accordingly, the absence of statistically significant positional effects, or interactions, should not be interpreted as evidence of equivalent load exposure across positions. Rather, the observed positional effect-size patterns should be considered exploratory and practice-oriented.

From a practical standpoint, the absence of significant ApP × position interactions suggests that ApP-related changes in external load occurred in broadly similar directions across positional roles, while playing role and individual capacity may still influence the magnitude of the response. This is consistent with density-based modelling showing that increasing ApP can increase high-speed exposure at squad level, but may still lead to under- or over-exposure for specific roles or individuals when uniform prescriptions are applied (Sangnier et al., 2019; Riboli et al., 2022). Therefore, practitioners should view ApP as a useful first-order programming variable for scaling high-intensity and metabolically demanding locomotor exposure, but should continue to monitor individual and position-specific responses, particularly in youth players undergoing rapid development, to ensure adequate and balanced exposure to HSR, sprinting, HMLD, and maximal-speed demands across the microcycle.

Several limitations should be acknowledged. First, biological maturity status was not assessed, which may partly explain the observed inter-individual variability in speed-related outcomes within a single age category, given the known influence of maturation on sprint capacity and tolerance to high-intensity load (Philippaerts et al., 2006; Hall et al., 2022). Second, although the repeated-measures observational design reflected an ecologically valid academy training environment, it limits causal inference; therefore, the observed ApP-related findings should be interpreted as associations rather than causal effects of density manipulation. Third, the number of training sessions was limited, although session-level clustering was accounted for in the mixed-effects models. Fourth, although the present analysis focused on external physical load, internal load and technical-tactical behaviours were not examined, and may have influenced locomotor and mechanical responses across ApP values and density conditions. Fifth, mechanical load was operationalised primarily through acceleration and deceleration counts. Alternative approaches using intensity-continuous thresholds, or additional inertial metrics, may reveal ApP-related effects not captured by the selected indicators (Vampola et al., 2025). Finally, because formal equivalence testing, minimal detectable change thresholds, or device-specific reliability-based bounds were not applied, non-significant associations for TD, ACC, and DEC should not be interpreted as evidence of true invariance, but rather as an absence of statistically detectable associations in the present dataset.

Future studies should integrate biological maturity assessment, and consider individualised speed thresholds to better contextualise high-intensity exposure during adolescence. Maturity-related differences in physical capacities may partly influence external load responses to different ApP conditions, and improve the practical interpretation of SSG design in elite youth football. Longitudinal designs are needed to determine how systematic exposure to different ApP prescriptions influences sprint capacity, injury risk, and performance development over time. Future research should also continue to model ApP as a continuous variable, while using density categories primarily for applied translation, to avoid loss of information caused by categorisation. Additionally, studies combining external physical load with internal load and technical-tactical indicators could clarify which rule constraints and interaction patterns most effectively modulate acceleration- and deceleration-based mechanical demands within SSGs (Sarmento et al., 2018; Clemente et al., 2023). Finally, larger datasets using position- and individual-specific modelling approaches are needed to verify whether the exploratory positional patterns observed in this study represent stable practical differences or sample-specific variability in elite youth environments.

Conclusion

Relative area per player (ApP) was positively associated with high-intensity locomotor, and metabolically demanding external load, during training-based small-sided games in elite U17 soccer players. Larger ApP values were associated with greater HSR, SPRINT, NSPRINTS, HMLD, and %MSPEED, whereas, no significant associations were observed for TD, ACC, or DEC. Playing position did not significantly moderate the association between ApP and external load, suggesting that ApP-related responses occurred in broadly similar directions across positional roles. However, supplementary player-level effect-size analyses indicated recurring exploratory practical positional patterns, particularly for high-speed, sprint-related, metabolic, and maximal-speed variables. From an applied perspective, ApP represents a useful and easily adjustable programming variable for scaling high-intensity locomotor exposure in elite youth soccer, although additional task constraints may be required when the aim is to specifically manipulate acceleration- and deceleration-based mechanical demands.

Acknowledgements

The work was supported by the Charles University Research Centre program No. UNCE24/SSH/012 and Cooperatio programs (Sport Sciences – Biomedical & Rehabilitation Medicine; Sport & Social). The authors have declared that there are no conflicts of interest in the authorship and publication of this contribution. The datasets generated and analyzed in this study are not publicly available but are available from the corresponding author who organized the study upon reasonable request. All experimental procedures were conducted in compliance with the relevant legal and ethical standards of the country where the study was performed. The authors declare that no Generative AI or AI-assisted technologies were used in the writing of this manuscript.

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Key points

- Larger ApP was associated with greater high-speed running, sprint distance, sprint frequency, HMLD, and maximal-speed exposure.
- ApP was not significantly associated with total distance, accelerations, or decelerations.
- Playing position did not significantly moderate the association between ApP and external load.
- Exploratory effect-size analyses suggested practical positional patterns, particularly for high-speed and sprint-related variables.
- ApP is a practical tool for scaling locomotor intensity, but additional constraints may be needed to target acceleration- and deceleration-based demands.

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Supplementary Materials

Supplementary Table S1. Distribution of observations across playing positions and game density conditions.

Position	High density	Medium density	Low density	Total observations
CB	5	16	23	44
FB	19	25	40	84
W	16	27	39	82
CM	19	25	42	86
ST	8	14	22	44
Total	67	107	166	340

Values represent repeated player observations collected across multiple training sessions during the competitive season. The dataset included 7 high-density sessions, 8 medium-density sessions, and 13 low-density sessions. CB = central back; FB = full back; W = wide midfielder; CM = centre midfielder; ST = striker.

Supplementary Table S2. Selected positional effect sizes and recurring positional patterns across density conditions.

Density	Variable	Observed positional pattern	Comparison	Hedges' g	Magnitude
Low density	ACC	CM repeatedly differed from multiple positions	CM vs ST	0.58	moderate
Low density	ACC	CM repeatedly differed from multiple positions	FB vs CM	-0.53	moderate
Low density	DEC	W repeatedly differed from multiple positions	CB vs W	0.6	moderate
Low density	DEC	W repeatedly differed from multiple positions	W vs ST	0.58	moderate
Low density	HMLD	CB repeatedly differed from multiple positions	CB vs FB	0.87	large
Low density	HMLD	CB repeatedly differed from multiple positions	CB vs W	0.79	moderate
Low density	HMLD	CB repeatedly differed from multiple positions	CB vs ST	0.75	moderate
Low density	HMLD	CB repeatedly differed from multiple positions	CB vs CM	0.54	moderate
Low density	HSR	W repeatedly differed from multiple positions	W vs ST	1.29	large
Low density	HSR	W repeatedly differed from multiple positions	W vs CM	0.98	large
Low density	%MSPEED	Single dominant contrast	FB vs ST	0.71	moderate
Low density	NSPRINTS	CB repeatedly differed from multiple positions	CB vs ST	-1.3	large
Low density	NSPRINTS	CB repeatedly differed from multiple positions	CB vs W	-1.1	large
Low density	SPRINT	ST repeatedly differed from multiple positions	CB vs ST	-1.15	large
Low density	SPRINT	ST repeatedly differed from multiple positions	CM vs ST	0.73	moderate
Low density	SPRINT	ST repeatedly differed from multiple positions	FB vs ST	0.62	moderate
Low density	TD	FB repeatedly differed from multiple positions	CB vs FB	1.16	large
Low density	TD	FB repeatedly differed from multiple positions	FB vs CM	-0.76	moderate
Medium density	ACC	FB repeatedly differed from multiple positions	FB vs CM	-0.85	large
Medium density	ACC	FB repeatedly differed from multiple positions	FB vs W	-0.64	moderate
Medium density	DEC	FB repeatedly differed from multiple positions	FB vs ST	0.98	large
Medium density	DEC	FB repeatedly differed from multiple positions	FB vs W	-0.59	moderate
Medium density	HMLD	W repeatedly differed from multiple positions	W vs ST	-0.97	large
Medium density	HMLD	W repeatedly differed from multiple positions	FB vs W	0.89	large
Medium density	HMLD	W repeatedly differed from multiple positions	CB vs W	0.78	moderate
Medium density	HSR	W repeatedly differed from multiple positions	FB vs W	0.62	moderate
Medium density	HSR	W repeatedly differed from multiple positions	W vs CM	-0.53	moderate
Medium density	%MSPEED	FB repeatedly differed from multiple positions	FB vs ST	0.75	moderate
Medium density	%MSPEED	FB repeatedly differed from multiple positions	FB vs W	0.54	moderate
Medium density	NSPRINTS	W repeatedly differed from multiple positions	W vs CM	-0.9	large
Medium density	NSPRINTS	W repeatedly differed from multiple positions	FB vs W	0.89	large
Medium density	NSPRINTS	W repeatedly differed from multiple positions	W vs ST	0.57	moderate
Medium density	SPRINT	W repeatedly differed from multiple positions	W vs CM	-0.94	large
Medium density	SPRINT	W repeatedly differed from multiple positions	FB vs W	0.92	large
Medium density	TD	ST repeatedly differed from multiple positions	CM vs ST	-1.04	large
Medium density	TD	ST repeatedly differed from multiple positions	W vs ST	-1.01	large
High density	ACC	FB repeatedly differed from multiple positions	FB vs ST	0.87	large
High density	ACC	FB repeatedly differed from multiple positions	FB vs W	0.58	moderate
High density	DEC	FB repeatedly differed from multiple positions	CB vs FB	0.97	large
High density	DEC	FB repeatedly differed from multiple positions	FB vs W	0.84	large
High density	DEC	FB repeatedly differed from multiple positions	FB vs ST	0.74	moderate
High density	HMLD	FB repeatedly differed from multiple positions	FB vs W	0.99	large
High density	HMLD	FB repeatedly differed from multiple positions	CB vs FB	-0.79	moderate
High density	HMLD	FB repeatedly differed from multiple positions	FB vs CM	0.73	moderate
High density	HSR	CB repeatedly differed from multiple positions	CB vs FB	-0.63	moderate
High density	HSR	CB repeatedly differed from multiple positions	CB vs W	-0.54	moderate
High density	HSR	CB repeatedly differed from multiple positions	CB vs ST	0.52	moderate
High density	%MSPEED	CB repeatedly differed from multiple positions	CB vs ST	1.02	large
High density	%MSPEED	CB repeatedly differed from multiple positions	CB vs FB	1.0	large
High density	%MSPEED	CB repeatedly differed from multiple positions	CB vs W	0.84	large
High density	%MSPEED	CB repeatedly differed from multiple positions	CB vs CM	0.6	moderate
High density	NSPRINTS	CB repeatedly differed from multiple positions	CB vs CM	-1.21	large
High density	NSPRINTS	CB repeatedly differed from multiple positions	CB vs FB	-0.96	large
High density	NSPRINTS	CB repeatedly differed from multiple positions	CB vs W	-0.88	large
High density	NSPRINTS	CB repeatedly differed from multiple positions	CB vs ST	0.51	moderate
High density	SPRINT	CB repeatedly differed from multiple positions	CB vs FB	-0.86	large
High density	SPRINT	CB repeatedly differed from multiple positions	CB vs W	-0.77	moderate
High density	SPRINT	CB repeatedly differed from multiple positions	CB vs CM	-0.65	moderate
High density	SPRINT	CB repeatedly differed from multiple positions	CB vs ST	0.51	moderate
High density	TD	W repeatedly differed from multiple positions	CB vs W	0.75	moderate
High density	TD	W repeatedly differed from multiple positions	FB vs W	0.71	moderate
High density	TD	W repeatedly differed from multiple positions	W vs ST	-0.57	moderate

Hedges' g values were calculated from player-level aggregated means to account for repeated observations. The table reports selected practically relevant positional contrasts ($0.50 \le |g| \le 1.30$), together with recurring positional patterns observed within density conditions. Recurring positional patterns were identified when one position demonstrated practically relevant contrasts against multiple other positions within the same variable and density condition. These findings should be interpreted as exploratory practical patterns rather than evidence of statistically significant ApP × position interactions, as no interaction effects reached statistical significance in the multilevel mixed-effects models. Magnitude thresholds: trivial <0.20; small 0.20 - 0.49; moderate 0.50 - 0.79; large ≥0.80; CB = central back; FB = full back; W = wide midfielder; CM = centre midfielder; ST = striker.