Capturing homeostatic behaviour in elite football teams: synchronisation tendencies of cooperative and oppositional dynamics

SANTOS, Ricardo, GARGANTA, Júlio, LOPES, Rui J, DAVIDS, Keith <http://orcid.org/0000-0003-1398-6123> and RIBEIRO, João

---

This document is the Accepted Version [AM]

Citation:

SANTOS, Ricardo, GARGANTA, Júlio, LOPES, Rui J, DAVIDS, Keith and RIBEIRO, João (2026). Capturing homeostatic behaviour in elite football teams: synchronisation tendencies of cooperative and oppositional dynamics. International Journal of Data Science and Analytics, 21 (10). [Article]

Capturing homeostatic behaviour in elite football teams: Synchronisation tendencies of cooperative and oppositional dynamics

Ricardo Santos[1*], Júlio Garganta[1], Rui J. Lopes[2,3], Keith Davids[4], João Ribeiro[1]

[1]CIFI2D, Centre of Research, Education, Innovation and Intervention in Sport, Faculdade de Desporto, Universidade do Porto, Rua Dr. Plácido Costa, 91, 4200-450 Porto, Portugal
[2]Iscte, Lisboa, Portugal
[3]Instituto de Telecomunicações, Lisboa, Portugal.
[4]Sport & Human Performance research group, Sheffield Hallam University, Collegiate Campus, Broomgrove Road, Sheffield S10 2LX, UK
*Corresponding author e-mail: ricardosantos1.0@hotmail.com
Rua Dr. Plácido Costa, 91, 4200-450 Porto, Portugal
Telephone: +351 225074700; Fax: +351 225500687

Funding: Rui J. Lopes was partly supported by FCT – Fundação para a Ciência e Tecnologia, I.P. by project reference UIDB/50008/2020, and DOI identifier https://doi.org/10.54499/UIDB/50008/2020 awarded to Instituto de Telecomunicações.

Abstract:

This study, investigating the collective homeostasis model, explores the importance of understanding both individual and collective behaviors in analysis of team performance in sport. Rooted in ecological dynamics, this model views collective behaviors in sports teams as a homeostatic process, with structural integrity of performance empowered through synergistic actions at multiple levels. At the micro-level, players interact with their nearest teammates (at a meso-level) through n-ary interpersonal relations, producing complex behaviors or synergetic patterns observable at the macro-level. These patterns, and their level of synchronisation, reflect microscopic homeostatic regulation, directly impacting team stability. Here, we sought to capture micro homeostasis effects (reflected in the meso-level of behaviors) in football teams by analysing synchronisation tendencies of simplice structures, regulated by information that emerges on players' angles and distance to goal. Frequency of simplice patterning during a game, the influence of ball possession, and effects of size and type of simplices on synchronisation tendencies, are all crucial to understanding how collective homeostasis is regulated within a competitive sports team, mirroring the synergistic processes that underpin effective teamwork.

Keywords: Collective homeostasis; Micro homeostasis; Simplices; Synchronisation tendencies; Angle and Distance to goal; Football

1. Introduction

Understanding individual and collective behaviours that underpin team coordination in sports is crucial for success [1-3]. The collective homeostasis model, recently developed by Santos and colleagues [4], offers a novel theoretical perspective on how individuals performing in a sports team regulate their behaviours dynamically in response to competitive demands. Grounded in ecological dynamics, this model suggests that collective behaviour emerges from homeostatic regulation, where players (as system components) continuously adapt actions (adapter component ability) to maintain structural integrity within survival parameters [4]. In a sports performance context, this process corresponds to effective collective system behaviour that adapts to varying competitive performance demands by exploiting synergetic behaviours across different levels of complexity [4].

According to this model, a system, such as a football team, exhibits homeostasis across multiple levels of analysis to maintain the function-performance outcome relationality. Specifically, homeostatic regulation occurs at the micro-level (player relationships) and meso-level (group synergies) – referred to as *micro homeostasis*, and macro-level (team interactions) – referred to as *macro homeostasis* [5]. Micro homeostasis consists of individualized effects allowing each player to co-adapt their behaviours during team performance [5]. Macro homeostasis, on the other hand, refers to maintaining balance and stability in collective performance at the team level [5]. It encompasses the integrated interactions between multiple subsystems (e.g., coordination of actions of defenders and attackers) to ensure the overall functionality and adaptability of the larger system (the team). At both levels, homeostatic regulation is facilitated by key information variables, such as interpersonal distances, approach velocities in co-adaptive movements of teammates and opponents, and available spatial affordances – opportunities for action; [6] [4, 5]. Additionally, distance and angle to the goal have been identified as critical spatiotemporal constraints impacting the emergence of team behaviours [7, 8].

As an adaptive competitive entity, a football team depends on micro homeostasis, subtended to the principle of collective homeostasis [5]. In these dynamic movement systems, homeostatic fluctuations emerge across different system levels, which is key to achieving adaptive reorganisation for performance optimization. This dynamic process reflects system degeneracy – the ability of different structural configurations to achieve functionally equivalent outcomes, allowing teams to maintain stability while adapting to performance demands [9-11].

From this perspective, player behaviours—whether expressed through dyadic or group-level couplings—can be interpreted as purposeful attempts to return the team to a dynamically stable state. These adjustments represent localised regulatory actions aimed at restoring balance within the system in response to continuously changing competitive performance demands. Thus, analysing these cooperative and oppositional structures provides insight into how players co-adapt their actions, not merely in transactions with emergent information, but as part of a larger collective effort to re-establish system-level homeostasis.

Notwithstanding the theoretical advancements in understanding collective homeostasis, empirical evidence on how these regulatory processes emerge in elite competition remains limited. Previous research has highlighted the relevance of analysing synchronisation tendencies emerging at team organisation's meso- and macro-levels (e.g., [12, 13]). In this regard, the study of Duarte et al. [12] reported that collective synchronisation is more pronounced along the longitudinal axis of the field. The close relationship between the synchronisation patterns of the two teams suggests that each team's behaviour directly influences the other, reflecting the interactive and dynamic nature of the game. Meanwhile, a study by Ribeiro et al. [13] found that manipulating specific constraints – such as the number, size, and positioning of goals – can influence meso-level synchronisation tendencies. In a similar perspective, other studies (e.g., Laakso et al. [14, 15]) have highlighted the importance of understanding the dynamics of player interactions at the meso-scale level, as well as examining synchronisation across different areas of the playing field [16].

Regardless, research has yet to ascertain how synchronisation tendencies, driven by cooperative and opposing relationships, reflect the homeostatic regulation of teams as they emerge and evolve during competition. Furthermore, little is known about how key game factors such as ball possession and the type and size of relational structures (also called simplices) influence this regulatory process and shape synchronisation tendencies during competitive performance.

In light of these findings, this study investigates homeostatic regulation by analysing synchronisation tendencies shaped by emerging information on the angle and distance to the goal. This study's aims are threefold: i) identify the most frequently occurring cooperative and opposing structures (simplices) during a game; ii) examine whether synchronisation tendencies vary as a function of ball possession and simplice size, given their potential influence on synchronisation; and iii), evaluate the synchronisation tendencies of the most frequently occurring simplices.

Based on previous research [17, 18] we hypothesise that 1vs.1, 1vs.2, and 2vs.1 structures would emerge more frequently. Moreover, we expect that synchronisation tendencies will be influenced by ball possession and simplice size, reflecting the dynamic changes in team coordination during offensive and defensive sub-phases of play.

2. Materials and methods

2.1 Materials

This work presents a case study, and the data was obtained through convenience sampling, meaning it was selected based on accessibility and availability. Two types of raw data are used in this paper: positional and notational data. The positional raw data consist of the longitudinal and lateral displacements (2D) of 28 male professional football players from two teams (11 starting players and 3 substitutes per team), recorded during performance in a professional league match, on a playing area, 68m wide by 105m long. These data were provided by STATS and obtained with a multiple-camera match analysis system, with frames processed at 1Hz via automated video file synchronisation. The validity and reliability of this tracking system has been quantified to verify the capture process and data accuracy [19, 20]. The notational data refers to ball possession status (team A, none, team B) with timestamps synchronized with the positional data and was performed by a single observer on two separate occasions, with an intra-observer kappa coefficient greater than 0.80, which is generally interpreted as indicating strong agreement [21].

2.2 Data pre-processing

The positional data was pre-processed with an interpolation method for imputation of missing positional data. The number of imputed positional values was below 0.5% of the total frames.

2.3 Ecological variables: simplices and pitch location

Cooperative and opposing relationships are represented as player subset structures, i.e., simplices, enumerating the players within the subset and the structure-team balance. Figure 1 illustrates player structures identified in a frame, namely, $\sigma_n = \{a_{18}, a_{28}, b_3, 2vs.1\}$ with two attacking (Team A – red) and one defending (Team B – blue) player, i.e., a 2vs.1 structure (size 3), $\sigma_i = \{a_{17}, b_8, 1vs.1\}$, with one attacking and one defending player, i.e., a 1vs.1 structure (size 2), and $\sigma_k = \{a_{16}, a_{23}, a_{24}, b_9, b_{13}, 3vs.2\}$ with three attacking and two defending players, i.e., a 3vs.2 structure (size 5). The relation between the players in a simplice is represented by a hyperedge connecting them.

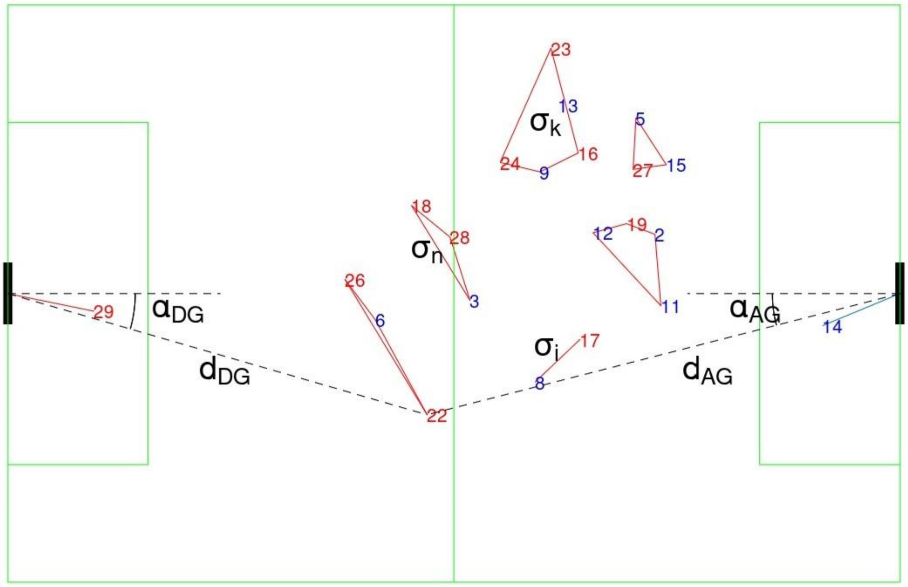


Figure 1 Schematic representation of player structures (simplices, player sets connected by hyperedges, e.g., $\sigma_n = \{a_{18}, a_{28}, b_3\ 2vs.1\}$), $\sigma_i = \{a_{17}, b_8\ 1vs.1\}$) $\sigma_k = \{a_{16}, a_{23}, a_{24}, b_9, b_{13}\ 3vs.2\}$) and analysis variables (distance and angle to attacked, d_{AG} and a_{AG}, defended goals, d_{DG} and a_{DG} represented for player a_{23}). The direction of the goal being attacked is from left to right.

Hyperedges are set with proximity-based criteria, such that each player is always in the same simplice as its closest player or goal (the algorithm for computing the simplices is presented in supplementary materials, Appendix A).

In this study we focus on how the synchronisation of the analysis variables between the players of each simplice depends on its location on the field. For this purpose, the field is divided over 6 longitudinal and 4 lateral field zones (defensive (DEF1-DEF2), midfield (MID1-MID2) and attacking (ATT2-ATT1) thirds) and the simplices' location defined by the zone containing its centre of mass.

2.4 Variables under analysis and their synchronisation

The analysis variables were defined as the distance and angle of each player in each simplice to the attacking and defending goals, d_{AG}, a_{AG}, d_{DG} and a_{DG}, as represented in Figure 1.

In the current study, the level of synchronisation can, thus, be computed using an extension to the process applied in the modelling of Ribeiro et al. [13] where the co-positioning of different *subgroups* (simplices) of players can be considered [22, 23], i.e., the level of synchronization ρ for simplice σ_n in frame k, regarding analysis variable v, $v \in \{d_{AG}, a_{AG}, d_{DG}, a_{DG}, d_{Long}, d_{Lat}\}$, is given by $\rho_{\sigma_{n},k,v} = \frac{1}{s_k}\left\|\sum_{p\in\sigma_n}\exp\left(i(\theta_{p,v}(k) - \bar{\theta}_{p,v}(k))\right)\right\|$, where s_k is the size of simplice σ_n, $\theta_{p,v}(k)$ is the phase of analysis variable v for player p at frame k and $\bar{\theta}_{p,v}(k)$ its mean over all the elements given by $\bar{\theta}_{p,v}(k) = \tan^{-1}\left(\frac{1}{s_k}\sum_{p\in\sigma_n}\exp\left(i\theta_{p,v}(k)\right)\right)$.

The phase, $\theta_{p,v}(k)$, of analysis variable v for player p at frame k is computed based on methods used by Varlet and Richardson [24], i.e., $\theta_{p,v}(k) = \tan^{-1}\left(\frac{v'_p(k)}{v_p(k)}\right)$, where $v_p(k)$ is the value of analysis variable v for player p at frame k and $v'_p(k)$ its period normalised time derivative.

2.5 Statistical methods

Computer procedures for computing the simplice hyperedges, analysis variables and the synchronisation values were evaluated using procedures developed by the authors in GNU Octave version 4.4.1 and applied to each match frame.

The effect of different factors (possession team, simplice type and simplice size) on the synchronisation values are assessed using three different methods: pairwise difference between means, pairwise rank differences and boxplots.

Due to the skewed distribution and size of the dataset, the statistical significance, *p*-value (two-sided), for the differences between means is computed via a permutation test method [25], using the stats.permutation_test function from SciPy 1.15.1 module for Python 3.11.1.

In the case of rank differences, the Brunner-Munzel statistic is used due to the different variances between the compared sets [26, 27]. The statistic value, its degrees of freedom, and *p*-value (computed with the two-sided *t* statistic) are computed using the stats.brunnermunzel function from SciPy 1.15.1 module for Python 3.11.1.

To provide a detailed comparison between the synchronisation values under the different factors box plot graphs with the usual quartile and interquartile marks are generated using the function boxplot from seaborn 0.12.2 module for Python 3.11.1.

3. Results

3.1 Number and frequency of simplices

Results presented in Figure 2 show the number of simplices in each of the 24 zones into which the football field was divided. The highest number of simplices is found in the midfield area, with a tendency for higher values on the right side of the midfield.

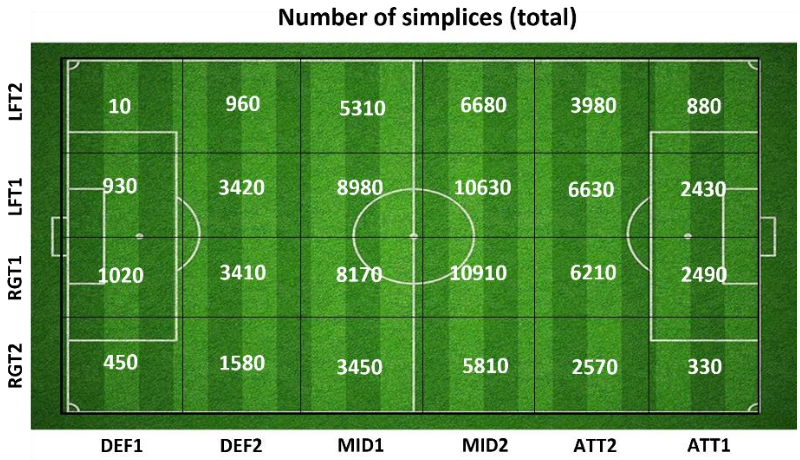
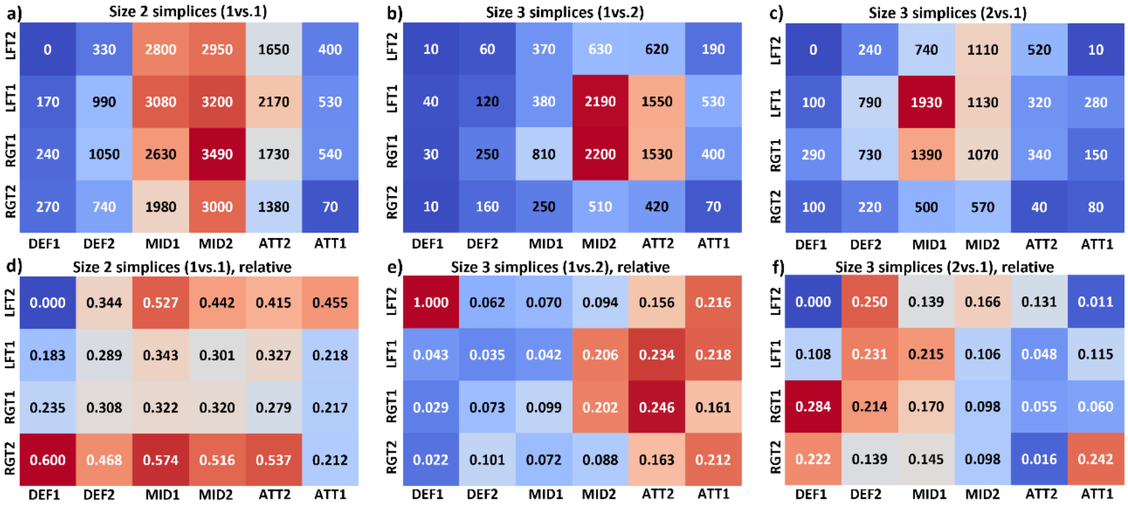


Figure 2 Representation of a football field with a total number of subsets (i.e., simplices) that occurred in each of the 24 zones. Field segmentation in 6 longitudinal (DEF – defensive third; MID – midfield third; ATT - attacking third) and 4 lateral zones (RGT – right side; LFT – left side)). The direction of the goal being attacked is from left to right.

Figures 3a, 3b and 3c represent the number of simplices for the most frequent structure type (1vs.1, 1vs.2 and 2vs.1) per field zone (the same relative values are displayed in Figures 3d, 3e and 3f).

The 1vs.1 structure emerged more frequently, particularly in the side corridors of the pitch (Figure 3d), whilst the 1vs.2 structure appeared more often near the attacked goal (Figure 3e). Interestingly, in one area of the field (DEF1-LFT2, Figure 3e), all observed simplices are 1vs.2 structures, possibly indicating the emergence of defensive imbalances. The 2vs.1 structure showed higher values in the central corridor near the defended goals (Figure 3f), probably reflecting the defending teams' strategies to create numerical superiority (overload) in this critical area of the field to protect the goal.



a) Size 2 simplices (1vs.1)

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2	0	330	2800	2950	1650	400
LFT1	170	990	3080	3200	2170	530
RGT1	240	1050	2630	3490	1730	540
RGT2	270	740	1980	3000	1380	70

b) Size 3 simplices (1vs.2)

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2	10	60	370	630	620	190
LFT1	40	120	380	2190	1550	530
RGT1	30	250	810	2200	1530	400
RGT2	10	160	250	510	420	70

c) Size 3 simplices (2vs.1)

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2	0	240	740	1110	520	10
LFT1	100	790	1930	1130	320	280
RGT1	290	730	1390	1070	340	150
RGT2	100	220	500	570	40	80

d) Size 2 simplices (1vs.1), relative

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2	0.000	0.344	0.527	0.442	0.415	0.455
LFT1	0.183	0.289	0.343	0.301	0.327	0.218
RGT1	0.235	0.308	0.322	0.320	0.279	0.217
RGT2	0.600	0.468	0.574	0.516	0.537	0.212

e) Size 3 simplices (1vs.2), relative

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2	1.000	0.062	0.070	0.094	0.156	0.216
LFT1	0.043	0.035	0.042	0.206	0.234	0.218
RGT1	0.029	0.073	0.099	0.202	0.246	0.161
RGT2	0.022	0.101	0.072	0.088	0.163	0.212

f) Size 3 simplices (2vs.1), relative

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2	0.000	0.250	0.139	0.166	0.131	0.011
LFT1	0.108	0.231	0.215	0.106	0.048	0.115
RGT1	0.284	0.214	0.170	0.098	0.055	0.060
RGT2	0.222	0.139	0.145	0.098	0.016	0.242

Figure 3 Heat-maps representing the number of occurrences regarding: a) simplices 1vs.1; b) simplices 1vs.2; c) simplices 2vs.1; and the density (%) regarding: d) simplices 1vs.1; e) simplices 1vs.2; f) simplices 2vs.1. Values of density range from 0 (a smaller number of simplices) to 1 (highest number of simplices). The direction of the goal being attacked is from left to right.

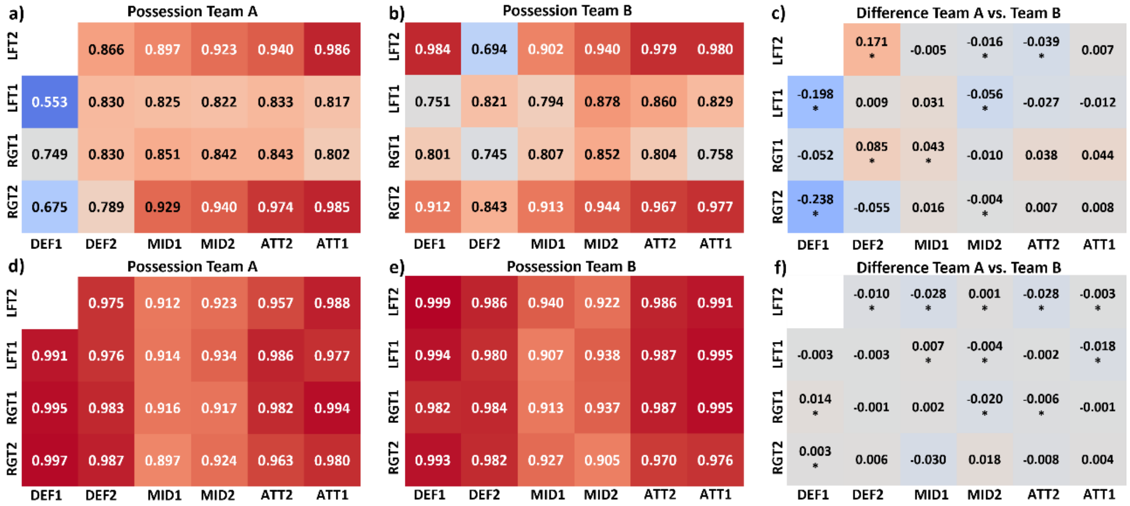
3.2 Synchronisation tendencies considering the effects of angle and distance to the goal

The remainder of this section analyses synchronisation tendencies by exploring the influence of ball possession, simplice size (i.e., the number of players involved in each simplice), and the type of simplice structure (i.e., simplice configuration – 1vs.1, 1vs.2 and 2vs.1).

3.2.1 Ball possession effect

When comparing synchronisation tendencies between the angle to the attacked goal (Figures 4a and 4b) and distance to the attacked goal (Figures 4d and 4e), it is evident that the highest values for angle synchronisation are found in the side corridors. For distance, the highest values emerge in the areas close to the goals (both offensive and defensive). Blank areas of the playing field indicate that team A did not exhibit any simplice configurations in those zones.

Regarding ball possession, angle synchronisation tendencies show greater variability (Figure 4c) compared to distance synchronisation (Figure 4f). However, statistically significant differences in the distance to the goal were observed across a larger number of playing field zones (12 zones), compared to the angle variable (9 zones) (detailed results are provided in Tables 1 and 2 of the supplementary materials).



a) Possession Team A

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.866	0.897	0.923	0.940	0.986
LFT1	0.553	0.830	0.825	0.822	0.833	0.817
RGT1	0.749	0.830	0.851	0.842	0.843	0.802
RGT2	0.675	0.789	0.929	0.940	0.974	0.985

b) Possession Team B

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2	0.984	0.694	0.902	0.940	0.979	0.980
LFT1	0.751	0.821	0.794	0.878	0.860	0.829
RGT1	0.801	0.745	0.807	0.852	0.804	0.758
RGT2	0.912	0.843	0.913	0.944	0.967	0.977

c) Difference Team A vs. Team B

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.171 *	-0.005	-0.016 *	-0.039 *	0.007
LFT1	-0.198 *	0.009	0.031	-0.056 *	-0.027	-0.012
RGT1	-0.052	0.085 *	0.043 *	-0.010	0.038	0.044
RGT2	-0.238 *	-0.055	0.016	-0.004 *	0.007	0.008

d) Possession Team A

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.975	0.912	0.923	0.957	0.988
LFT1	0.991	0.976	0.914	0.934	0.986	0.977
RGT1	0.995	0.983	0.916	0.917	0.982	0.994
RGT2	0.997	0.987	0.897	0.924	0.963	0.980

e) Possession Team B

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2	0.999	0.986	0.940	0.922	0.986	0.991
LFT1	0.994	0.980	0.907	0.938	0.987	0.995
RGT1	0.982	0.984	0.913	0.937	0.987	0.995
RGT2	0.993	0.982	0.927	0.905	0.970	0.976

f) Difference Team A vs. Team B

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		-0.010 *	-0.028 *	0.001 *	-0.028 *	-0.003 *
LFT1	-0.003	-0.003	0.007 *	-0.004 *	-0.002	-0.018 *
RGT1	0.014 *	-0.001	0.002	-0.020 *	-0.006 *	-0.001
RGT2	0.003 *	0.006	-0.030	0.018	-0.008	0.004

Figure 4 Illustration of heat-maps representing the simplices' synchronisation tendencies regarding: a) angle to attacked goal – team A with ball possession; b) angle to attacked goal – team B with ball possession; c) differences between angle to attacked goal considering ball possession; d) distance to attacked goal – team A with ball possession; e) distance to attacked goal – team B with ball possession; f) differences between distance to attacked goal considering ball possession. Values of synchronisation range from 0 (unsynchronised behaviour) to 1 (complete synchronised behaviour). The direction of the goal being attacked is from left to right. *Areas in which statistically significant differences were observed.

To facilitate the interpretation of synchronisation differences between team A and team B, Figures 5 and 6 illustrate the distribution of angle and distance synchronisation tendencies, respectively, toward the attacked goal across the 24 zones of the playing field.

Regarding the distribution of angle synchronisation (Figure 5), in the side corridors, as average synchronisation tendencies increase, variability in the distribution of synchronisation tendencies decreased for both teams as they approached the goal during an attack. In the central corridor, synchronisation tendencies showed greater levels of variability, regardless of the playing field area or the team in possession.

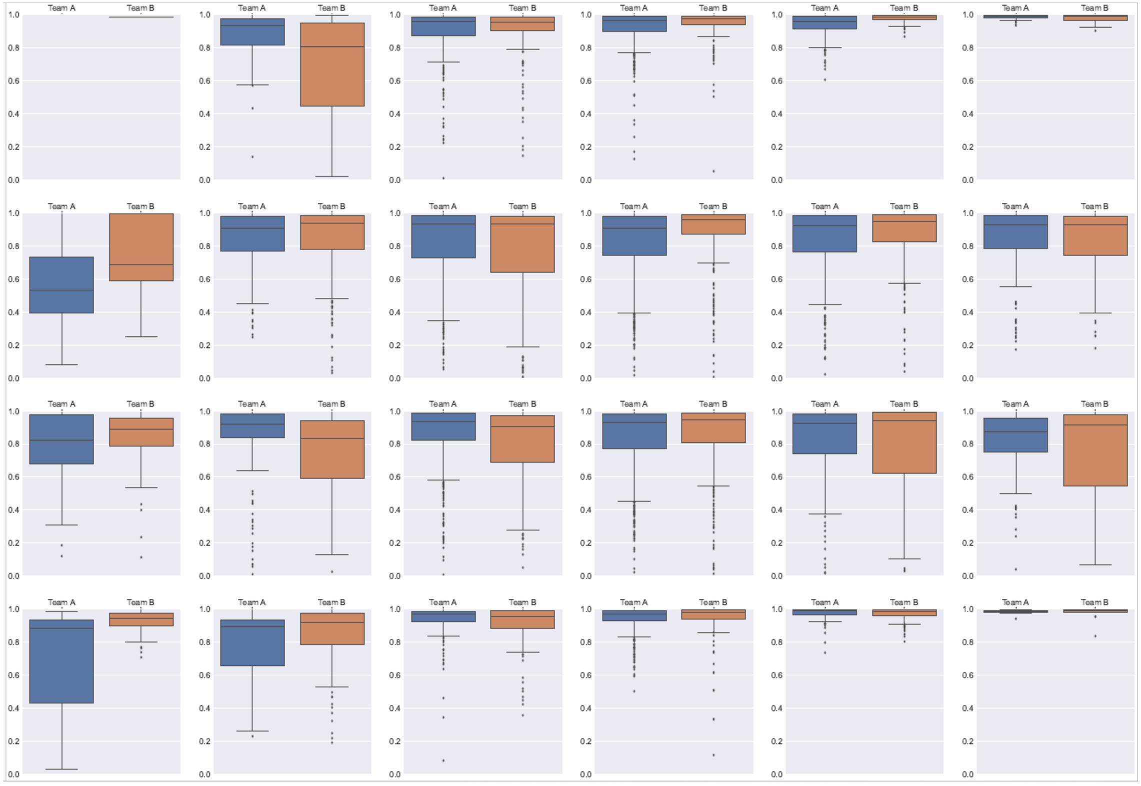


Figure 5 Illustration of box plots showing the distribution of synchronisation tendencies of team A and B during ball possession, relative to the angle to the attacked goal. The direction of the goal being attacked is from left to right.

Figure 6 illustrates that the distribution of synchronisation tendencies relative to the distance to the attacked goal shows greater variability in the midfield zone for both Teams A and B. As they approach the goal, this variation tends to decrease considerably.

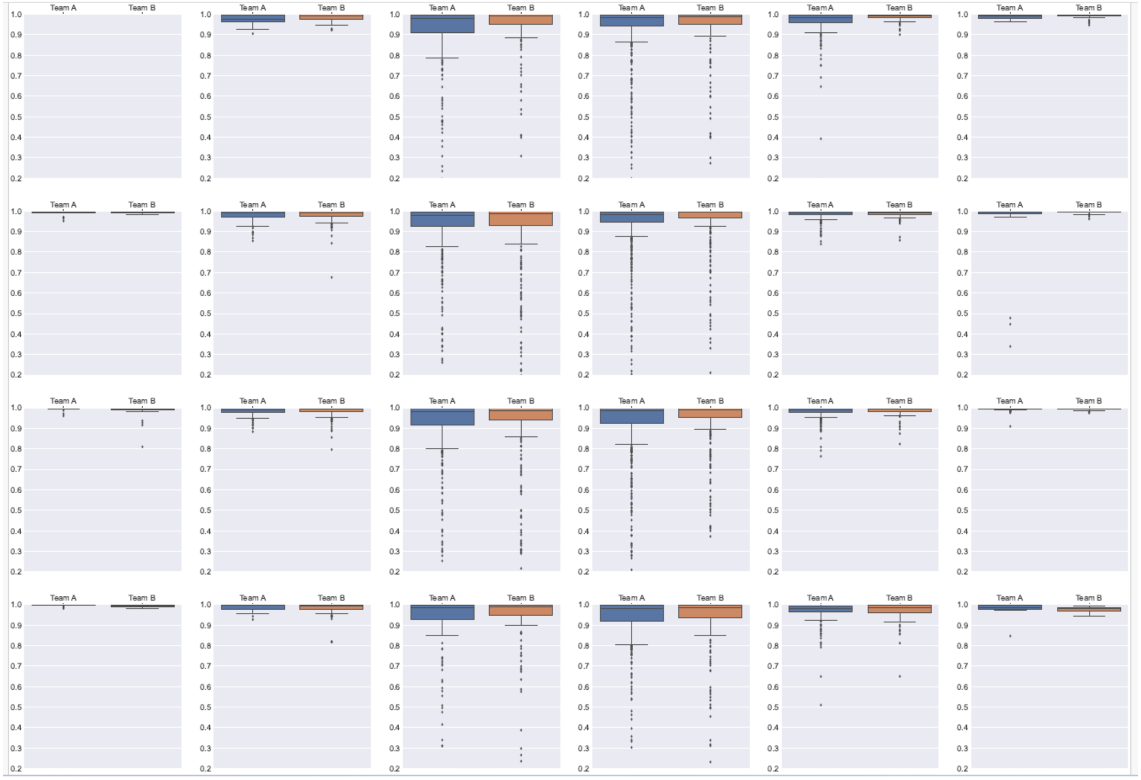
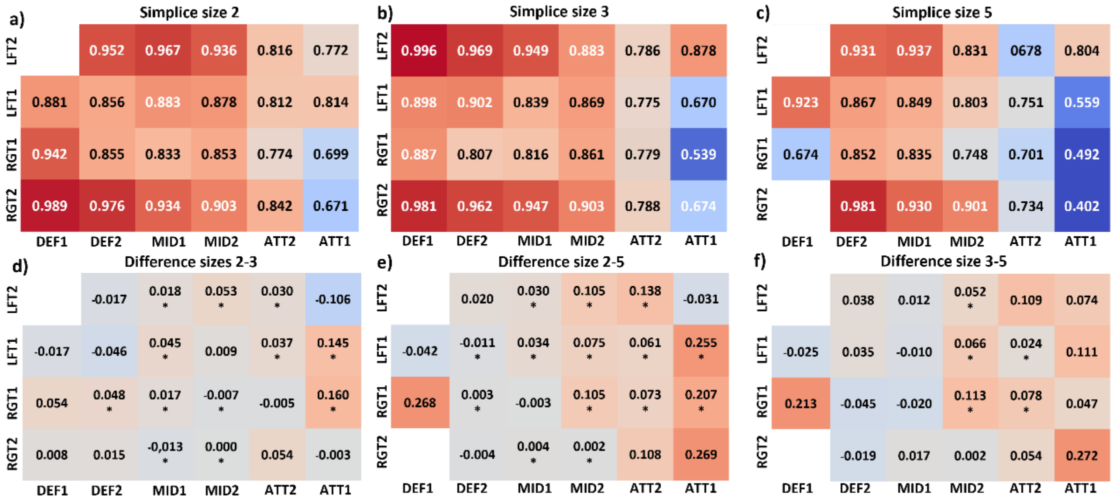


Figure 6 Illustration of box plots showing the distribution of synchronisation tendencies of team A and B during ball possession, relative to the distance to the attacked goal. The direction of the goal being attacked is from left to right.

3.2.2 Simplice's size effect

To better understand the results presented below, it is essential to clarify that the *simplice size 2* indicates that the structure comprises two players. The possible configurations for this simplice size are 1vs.1, 2vs.0 and 0vs.2. This interpretation applies similarly to other simplice sizes.

The variable, angle to the defending goal, was used to analyse differences in synchronisation tendencies shaped by simplice size. Figure 7a shows that simplices with size 2 present higher synchronisation tendencies in almost all areas of the field compared to simplices with size 3 (Figure 7b) and simplices with size 5 (Figure 7c). Figures 7d, 7e and 7f illustrate the differences in synchronisation tendencies between simplices 2 and 3 (2-3); 2 and 5 (2-5); and 3 and 5 (3-5), respectively, confirming that the larger simplices exhibit greater significantly differences compared to the smallest simplices of size 2 (detailed results are provided in Tables 3, 4 and 5 in the supplementary materials). Therefore, it is observed that, as the size of the simplices increases, the synchronisation tendency decreases.



a) Simplice size 2

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.952	0.967	0.936	0.816	0.772
LFT1	0.881	0.856	0.883	0.878	0.812	0.814
RGT1	0.942	0.855	0.833	0.853	0.774	0.699
RGT2	0.989	0.976	0.934	0.903	0.842	0.671

b) Simplice size 3

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2	0.996	0.969	0.949	0.883	0.786	0.878
LFT1	0.898	0.902	0.839	0.869	0.775	0.670
RGT1	0.887	0.807	0.816	0.861	0.779	0.539
RGT2	0.981	0.962	0.947	0.903	0.788	0.674

c) Simplice size 5

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.931	0.937	0.831	0678	0.804
LFT1	0.923	0.867	0.849	0.803	0.751	0.559
RGT1	0.674	0.852	0.835	0.748	0.701	0.492
RGT2		0.981	0.930	0.901	0.734	0.402

d) Difference sizes 2-3

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		-0.017	0.018 *	0.053 *	0.030 *	-0.106
LFT1	-0.017	-0.046	0.045 *	0.009	0.037 *	0.145 *
RGT1	0.054	0.048 *	0.017 *	-0.007 *	-0.005	0.160 *
RGT2	0.008	0.015	-0,013 *	0.000 *	0.054	-0.003

e) Difference size 2-5

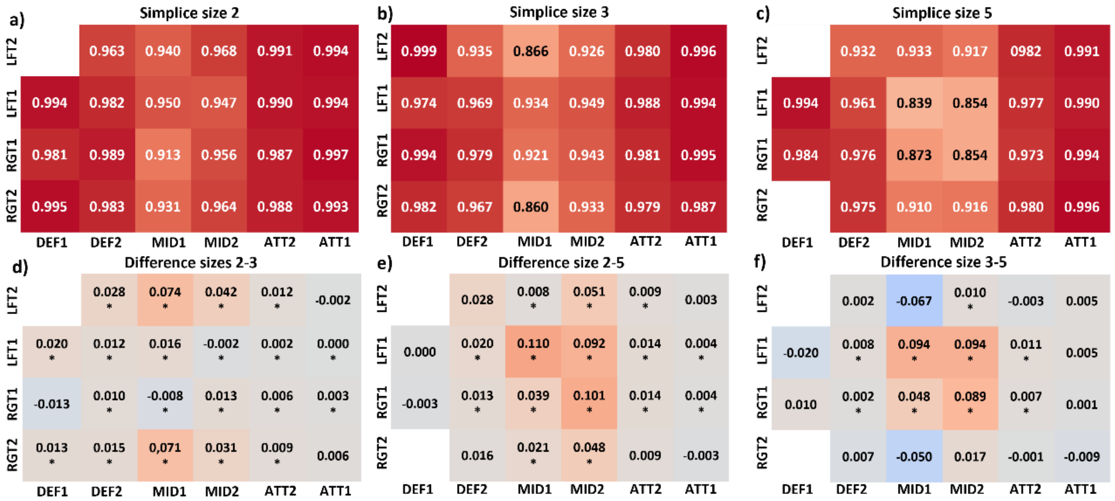
	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.020	0.030 *	0.105 *	0.138 *	-0.031
LFT1	-0.042	-0.011 *	0.034 *	0.075 *	0.061 *	0.255 *
RGT1	0.268	0.003 *	-0.003	0.105 *	0.073 *	0.207 *
RGT2		-0.004	0.004 *	0.002 *	0.108	0.269

f) Difference size 3-5

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.038	0.012	0.052 *	0.109	0.074
LFT1	-0.025	0.035	-0.010	0.066 *	0.024 *	0.111
RGT1	0.213	-0.045	-0.020	0.113 *	0.078 *	0.047
RGT2		-0.019	0.017	0.002	0.054	0.272

Figure 7 Illustration of heat-maps representing the simplices' synchronisation tendencies regarding: a) angle to defended goal – simplices size 2; b) angle to defended goal – simplices size 3; c) angle to defended goal – simplices size 5; d) differences between simplices size 2 and 3 considering angle to defended goal; e) differences between simplices size 2 and 5 considering angle to defended goal; f) differences between simplices size 3 and 5 considering angle to defended goal. Values of synchronisation range from 0 (unsynchronised behaviour) to 1 (complete synchronised behaviour). The direction of the goal being attacked is from left to right. *Areas in which statistically significant differences were observed.

Regarding the distance to the defended goal, Figure 8a shows that simplices with size 2 exhibit higher synchronisation tendencies across almost areas of the field when compared to simplices with size 3 (Figure 8b) and simplices with size 5 (Figure 8c), consistent with the patterns previously observed for the angle to the goal. Figures 8d, 8e and 8f further illustrate the differences in synchronisation tendencies between simplices sizes 2 and 3 (2-3); 2 and 5 (2-5); and 3 and 5 (3-5), respectively. These comparisons confirm that the larger simplices exhibit greater significant differences compared to the smallest simplices of size 2 (detailed results are provided in Tables 6, 7 and 8 in the supplementary materials).


a) Simplice size 2

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.963	0.940	0.968	0.991	0.994
LFT1	0.994	0.982	0.950	0.947	0.990	0.994
RGT1	0.981	0.989	0.913	0.956	0.987	0.997
RGT2	0.995	0.983	0.931	0.964	0.988	0.993

b) Simplice size 3

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2	0.999	0.935	0.866	0.926	0.980	0.996
LFT1	0.974	0.969	0.934	0.949	0.988	0.994
RGT1	0.994	0.979	0.921	0.943	0.981	0.995
RGT2	0.982	0.967	0.860	0.933	0.979	0.987

c) Simplice size 5

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.932	0.933	0.917	0982	0.991
LFT1	0.994	0.961	0.839	0.854	0.977	0.990
RGT1	0.984	0.976	0.873	0.854	0.973	0.994
RGT2		0.975	0.910	0.916	0.980	0.996

d) Difference sizes 2-3

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.028 *	0.074 *	0.042 *	0.012 *	-0.002
LFT1	0.020 *	0.012 *	0.016 *	-0.002 *	0.002 *	0.000 *
RGT1	-0.013	0.010 *	-0.008 *	0.013 *	0.006 *	0.003 *
RGT2	0.013 *	0.015 *	0,071 *	0.031 *	0.009 *	0.006

e) Difference size 2-5

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.028	0.008 *	0.051 *	0.009 *	0.003
LFT1	0.000	0.020 *	0.110 *	0.092 *	0.014 *	0.004 *
RGT1	-0.003	0.013 *	0.039 *	0.101 *	0.014 *	0.004 *
RGT2		0.016	0.021 *	0.048 *	0.009	-0.003

f) Difference size 3-5

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.002	-0.067	0.010 *	-0.003	0.005
LFT1	-0.020	0.008 *	0.094 *	0.094 *	0.011 *	0.005
RGT1	0.010	0.002 *	0.048 *	0.089 *	0.007 *	0.001
RGT2		0.007	-0.050	0.017	-0.001	-0.009

Figure 8 Illustration of heat-maps representing the simplices' synchronisation tendencies regarding: a) distance to defended goal – simplices size 2; b) distance to defended goal – simplices size 3; c) distance to defended goal – simplices size 5; d) differences between simplices size 2 and 3 considering distance to defended goal; e) differences between simplices size 2 and 5 considering distance to defended goal; f) differences between simplices size 3 and 5 considering distance to defended goal. Values of synchronisation range from 0 (unsynchronised behaviour) to 1 (complete synchronised behaviour). The direction of the goal being attacked is from left to right. *Areas in which statistically significant differences were observed.

Figure 9 reveals that there is a large variation in angle synchronisation tendencies to the defended goal, depending on the simplice size and location on the playing field. These variations are more pronounced in the central corridor than in the side corridors. However, in both cases, the amplitude of the distribution tends to increase as the goal is approached during an attack. When comparing distribution across different simplice sizes, size 5 shows the greatest variation in nearly all areas of the playing field.

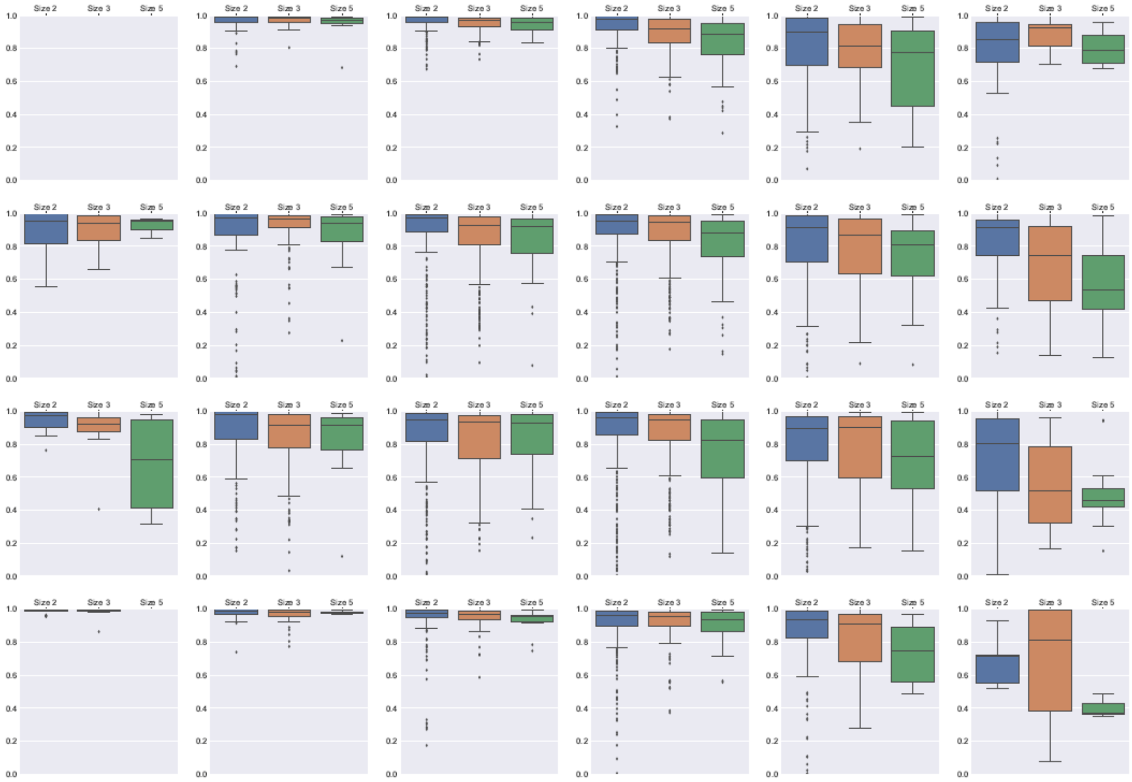


Figure 9 Illustration of box plots showing the distribution of synchronisation values of the simplices sizes 2, 3 and 5 with reference to the angle to the defended goal. The direction of the goal being attacked is from left to right.

Analysis of the values of distance to the defended goal (Figure 10) reveals considerable variation in synchronisation tendencies, particularly in zones near the midfield. When comparing distribution across different simplice sizes, structures of size 5 exhibit the greatest variation across the different areas of the playing field.

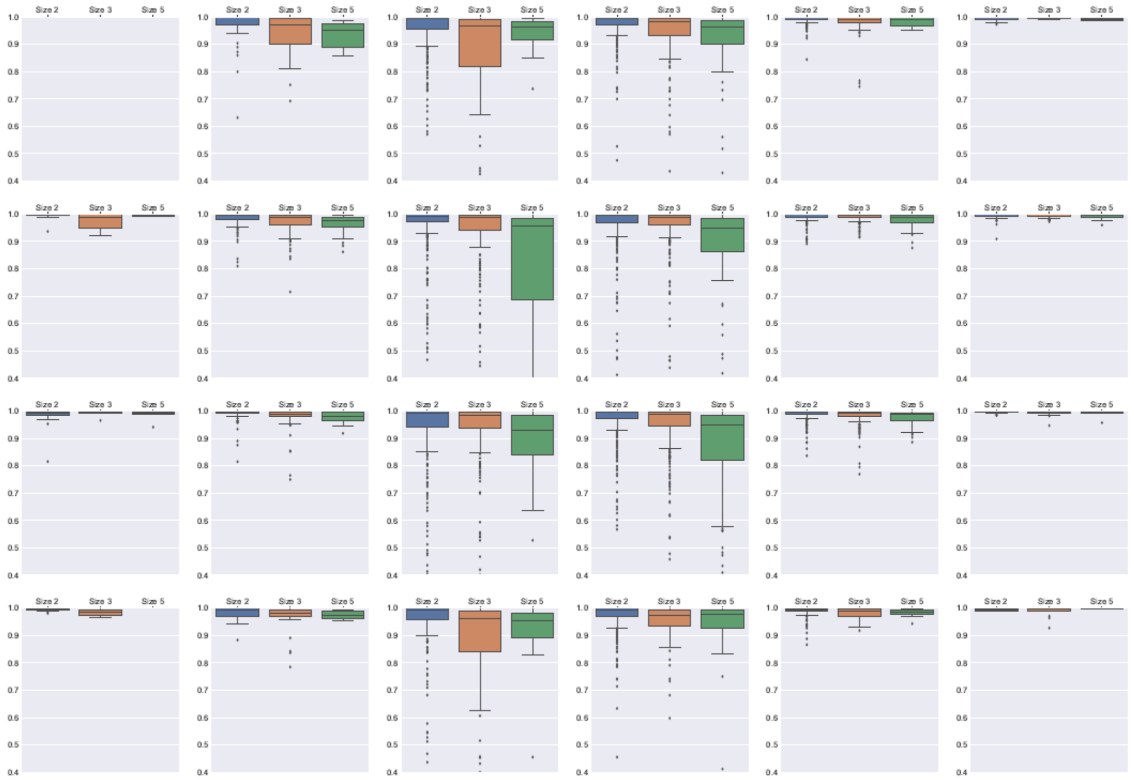


Figure 10 Illustration of box plots showing the distribution of synchronisation tendencies of the simplices sizes 2, 3 and 5 with reference to the distance to the defended goal. The direction of the goal being attacked is from left to right.

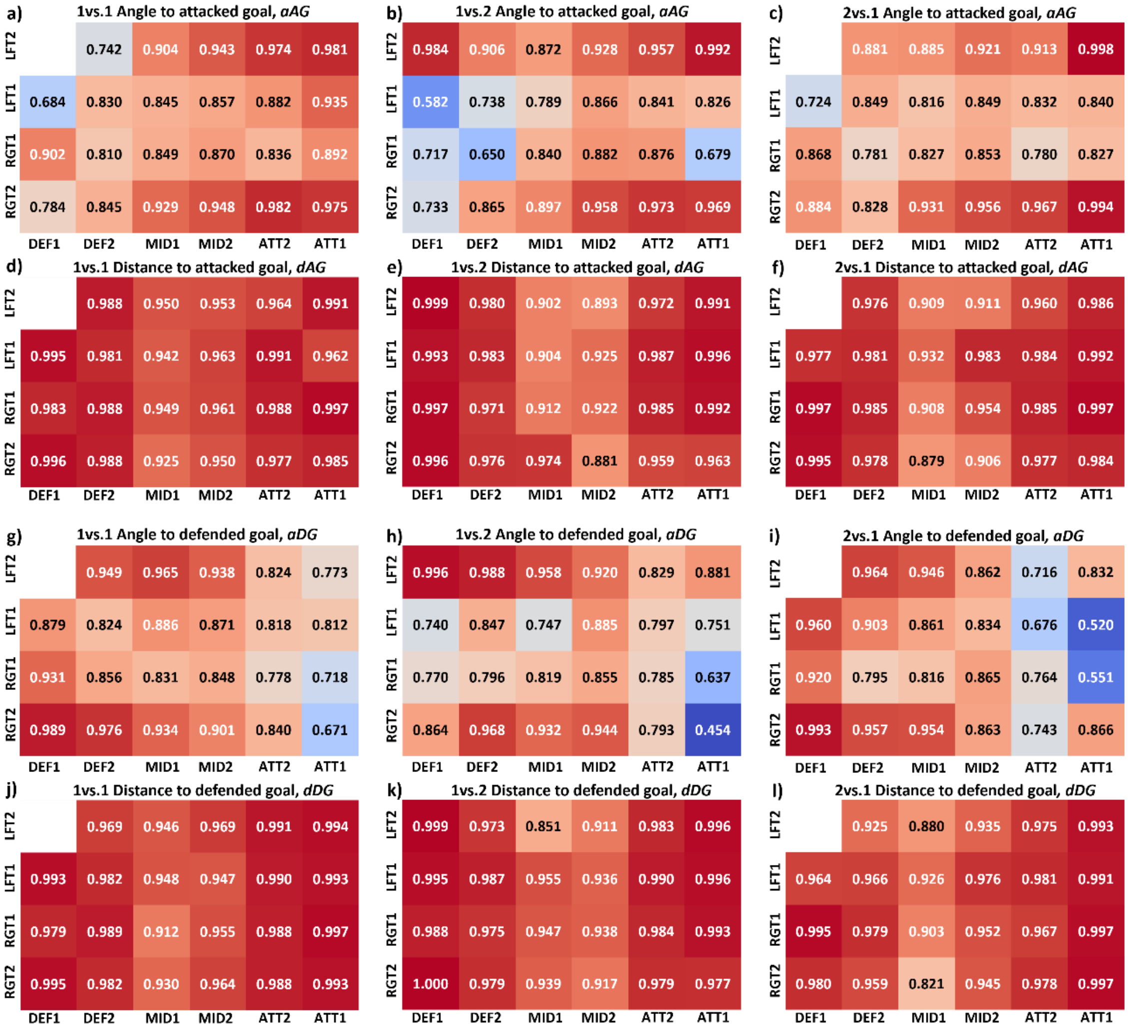
3.2.3 Structure type (1vs.1, 1vs.2 and 2vs.1) effect

When considering the effects of the value of the angle to the attacked goal (Figures 11a, 11b, and 11c), it was observed that synchronisation tendencies were higher in the side corridors of the playing field, particularly within the offensive midfield zone for all structure types (1vs.1, 1vs.2, and 2vs.1). For the angle to the defended goal (Figures 11g, 11h, and 11i), synchronisation tendencies were also higher in the side corridors, however, the tendencies are reversed, with the highest values observed near the defensive goal.

Regarding the value of the distance to the attacked goal (Figures 11d, 11e, and 11f), higher synchronisation tendencies were observed in areas closer to the goals in the 1vs.2 and 2vs.1 simplice structures. Although the 1vs.1 structure shows a similar trend to the 1vs.2 and 2vs.1 simplice structures, its synchronisation tendencies are more uniformly distributed across different areas of the field. For the value of the distance to the defended goal (Figures 11j, 11k, and 11l), similar tendencies to those described for the distance to the attacked goal were observed.

For both analysed variables, synchronisation tendencies vary based on the type of simplice structure and its location on field. When comparing synchronisation tendencies between the angle and distance to the goal, distance effects are generally higher.

Figures 11a, 11c, 11d, 11f, 11g, 11i, 11j, and 11l in the DEF1-LFT2 zone, do not show any synchronisation results, since in this specific area of the field, as previously mentioned, the formation of 1vs.1 and 2vs.1 simplices did not occur.



a) 1vs.1 Angle to attacked goal, *aAG*

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.742	0.904	0.943	0.974	0.981
LFT1	0.684	0.830	0.845	0.857	0.882	0.935
RGT1	0.902	0.810	0.849	0.870	0.836	0.892
RGT2	0.784	0.845	0.929	0.948	0.982	0.975

b) 1vs.2 Angle to attacked goal, *aAG*

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2	0.984	0.906	0.872	0.928	0.957	0.992
LFT1	0.582	0.738	0.789	0.866	0.841	0.826
RGT1	0.717	0.650	0.840	0.882	0.876	0.679
RGT2	0.733	0.865	0.897	0.958	0.973	0.969

c) 2vs.1 Angle to attacked goal, *aAG*

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.881	0.885	0.921	0.913	0.998
LFT1	0.724	0.849	0.816	0.849	0.832	0.840
RGT1	0.868	0.781	0.827	0.853	0.780	0.827
RGT2	0.884	0.828	0.931	0.956	0.967	0.994

d) 1vs.1 Distance to attacked goal, *dAG*

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.988	0.950	0.953	0.964	0.991
LFT1	0.995	0.981	0.942	0.963	0.991	0.962
RGT1	0.983	0.988	0.949	0.961	0.988	0.997
RGT2	0.996	0.988	0.925	0.950	0.977	0.985

e) 1vs.2 Distance to attacked goal, *dAG*

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2	0.999	0.980	0.902	0.893	0.972	0.991
LFT1	0.993	0.983	0.904	0.925	0.987	0.996
RGT1	0.997	0.971	0.912	0.922	0.985	0.992
RGT2	0.996	0.976	0.974	0.881	0.959	0.963

f) 2vs.1 Distance to attacked goal, *dAG*

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.976	0.909	0.911	0.960	0.986
LFT1	0.977	0.981	0.932	0.983	0.984	0.992
RGT1	0.997	0.985	0.908	0.954	0.985	0.997
RGT2	0.995	0.978	0.879	0.906	0.977	0.984

g) 1vs.1 Angle to defended goal, *aDG*

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.949	0.965	0.938	0.824	0.773
LFT1	0.879	0.824	0.886	0.871	0.818	0.812
RGT1	0.931	0.856	0.831	0.848	0.778	0.718
RGT2	0.989	0.976	0.934	0.901	0.840	0.671

h) 1vs.2 Angle to defended goal, *aDG*

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2	0.996	0.988	0.958	0.920	0.829	0.881
LFT1	0.740	0.847	0.747	0.885	0.797	0.751
RGT1	0.770	0.796	0.819	0.855	0.785	0.637
RGT2	0.864	0.968	0.932	0.944	0.793	0.454

i) 2vs.1 Angle to defended goal, *aDG*

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.964	0.946	0.862	0.716	0.832
LFT1	0.960	0.903	0.861	0.834	0.676	0.520
RGT1	0.920	0.795	0.816	0.865	0.764	0.551
RGT2	0.993	0.957	0.954	0.863	0.743	0.866

j) 1vs.1 Distance to defended goal, *dDG*

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.969	0.946	0.969	0.991	0.994
LFT1	0.993	0.982	0.948	0.947	0.990	0.993
RGT1	0.979	0.989	0.912	0.955	0.988	0.997
RGT2	0.995	0.982	0.930	0.964	0.988	0.993

k) 1vs.2 Distance to defended goal, *dDG*

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2	0.999	0.973	0.851	0.911	0.983	0.996
LFT1	0.995	0.987	0.955	0.936	0.990	0.996
RGT1	0.988	0.975	0.947	0.938	0.984	0.993
RGT2	1.000	0.979	0.939	0.917	0.979	0.977

l) 2vs.1 Distance to defended goal, *dDG*

	DEF1	DEF2	MID1	MID2	ATT2	ATT1
LFT2		0.925	0.880	0.935	0.975	0.993
LFT1	0.964	0.966	0.926	0.976	0.981	0.991
RGT1	0.995	0.979	0.903	0.952	0.967	0.997
RGT2	0.980	0.959	0.821	0.945	0.978	0.997

Figure 11 Illustration of heat-maps representing the simplices' synchronisation tendencies regarding: a) angle to attacked goal – 1vs.1; b) angle to attacked goal – 1vs.2; c) angle to attacked goal – 2vs.1; d) distance to attacked goal – 1vs.1; e) distance to attacked goal – 1vs.2; f) distance to attacked goal – 2vs.1; g) angle to defended goal – 1vs.1; h) angle to defended goal – 1vs.2; i) angle to defended goal – 2vs.1; j) distance to defended goal – 1vs.1; k) distance to defended goal – 1vs.2; l) distance to defended goal – 2vs.1. Values of synchronisation range from 0 (unsynchronized behaviour) to 1 (complete synchronised behaviour). The direction of the goal being attacked is from left to right.

4. Discussion

This study investigated homeostatic regulation by analysing the most frequent simplices (relational structures) and their synchronisation tendencies concerning their angle and distance to the goal. Additionally, the study examined whether synchronisation tendencies are influenced by ball possession and simplice size.

To achieve this, we employed a combined method of synchronisation analysis using variables of angle and distance to the goal alongside a multilevel hypernetworks approach [28]. This method allowed for a comprehensive analysis of the frequency and distribution of different simplice types across various field areas. Moreover, it enabled us to observe how specific subgroups of players exploit space during competitive performance.

Our findings confirmed the study's hypotheses. Specifically, the analysis revealed that 1vs.1, 1vs.2, and 2vs.1 structures occur most frequently, consistent with findings reported by Ramos et al. [17] and Ribeiro et al. [18]. These structures show higher relative frequency in specific field areas: 1vs.1 in the side corridors of the field, 1vs.2 near the attacking goal, and 2vs.1 in the central corridor near the defending goal. Interestingly, in the study by Ramos et al. [17], it was observed that, although there is some variation across different games in the locations where these structures occur, 1vs.1 structure tends to be more prevalent in the lateral corridors, while 2vs.1 structure is more frequent in the central corridor. These frequent configurations can be interpreted as emergent, functional units that players repeatedly rely on to regulate local interactions. Their recurrence in similar spatial locations suggests that they form part of purposeful, collective attempts to stabilise team structure under varying performance demands—an essential feature for maintaining system homeostasis.

Our data highlight how teams exhibit adaptive behaviours, illustrating, for example, how they create advantageous conditions through numerical superiority near the defending goal. Similar findings were observed in the study by Vilar et al. [3], who reported more players in areas near the defending goal. A higher frequency of 2vs.1 situations near the defending goal suggests that the defending team prioritises space control in critical field areas, thus mitigating the attacking team's ability to exploit gaps for goal-scoring opportunities.

On the other hand, our analysis revealed that ball possession and simplices' size and type influenced synchronisation tendencies. Specifically, during ball possession, for the distance to the goal, significant differences between teams were observed across a greater number of field zones, particularly in the left and central corridors, where Team B consistently showed higher synchronisation. Regarding the angle to the goal, the most pronounced differences between teams occurred predominantly in zones closer to the defensive goal and in the midfield area, with Team B displaying a tendency for higher synchronisation values. Overall, ball possession consistently influenced synchronisation tendencies in both variables. These results reflect how teams may adjust spatio-temporal behaviours as a function of the game phase, revealing the dynamic reorganisation processes that underpin adaptive regulation. This finding supports the idea that ball possession plays a central role in modulating homeostatic responses at the meso-level of team organisation. Similar findings have been reported by López-Felip et al. [7] and Ribeiro et al. [13], who noted variations in synchronisation tendencies, depending on ball possession. However, it is important to note that our study differs from that of Ribeiro et al. [13], who conducted their analysis in two modified game conditions, involving the manipulation of the number, location and size of goals, rather than in an 11vs.11 official competitive match. This variability in synchronisation patterns to information from the distance and angle to the goal highlights the important role of ball possession in shaping cooperative and oppositional movement dynamics between players. However, these findings contrast with those reported by Duarte et al. [12], who applied a traditional synchronisation model based on lateral and longitudinal player movements and found that ball possession did not affect collective team synchronisation. Our results suggest players needed to co-adapt their behaviours to changing performance constraints to achieve competitive goals [29, 30]. Also, the observed differences between teams may reflect distinct tactics and strategies (directly linked to other components of the collective homeostasis model – *identifier* and *set point*), which should be explored in future research.

Analysis of synchronisation tendencies concerning simplice size also yields interesting results. As the simplice size increases, synchronisation tendencies show a noticeable decrease. This suggests that larger subgroups of players involved in a performance sub-phase (e.g., attacking, defending, and transitioning) face greater challenges in maintaining high levels of synchronisation. Indeed, Garganta et al. [31] argue that as the number of players increases, the game situation becomes more complex due to the increasing number and quality of dynamic interpersonal relationships. Such evolving dynamics emerge from the formation of interpersonal synergies that aim to create favourable conditions for the attacking and defending teams regarding numerical, spatial, and temporal constraints. On the other hand, this decline in synchronisation may also be due to intentional counter-movements that disrupt defensive balance and create space for teammates.

During the competition, players temporarily assemble into group synergies to achieve specific performance goals [32, 33]. As the number of players increases, variations in synchronisation tendencies reveal how attacking players continually reorganize and adjust their functional behavioural patterns to destabilise the defensive structure of teams, while defenders attempt to maintain stability. Further research is needed to investigate the specific conditions under which synchronisation declines, and its positive and negative impacts on overall team coordination and performance outcomes.

Given the uniqueness and unpredictability of each game, teams need to demonstrate flexibility in their performance behaviours to adapt effectively to changing competitive demands [34, 35]. This behavioural flexibility is essential, whether shaped by opposition behaviours or required tactical adjustments. Such flexibility is commonly manifested through the emergence of interpersonal synergies, as players synchronise their behaviours in response to evolving competitive demands [36-38]. Enhancing homeostatic regulation by optimizing adaptive capacity (i.e. response variability), could improve stability at higher temporal and spatial organisation levels within the team system [39].

The analysis of 1vs.1, 1vs.2, and 2vs.1 simplices concerning distance and angle to the goal revealed variations in synchronisation tendencies across field zones. For instance, in terms of distance to the goal, higher synchronisation tendencies were observed in areas closer to the goals, particularly in the 1vs.2 and 2vs.1 structures. These critical zones show high levels of spatial coordination, as both teams aim to synchronise their movements to control or exploit space near the goal. While the 1vs.1 context follows a similar pattern, its synchronisation values seem more uniformly distributed across the field.

Regarding the angle to the goal, synchronisation tendencies were higher in the side corridors, across all structure types (1vs.1, 1vs.2, and 2vs.1). These patterns are likely the result of diagonal movements, in which attacking players attempt to break through the defence either from the outside corridors to the inside or vice versa. At the same time, defenders respond by tracking the player’s run (e.g., during 1-2 passing combinations) or by positioning themselves to neutralize passing lanes and restrict shooting opportunities.

This context-specific emergence of synchronisation aligns with the idea of adaptive micro- and meso-level fluctuations that help re-establish team equilibrium following perturbations, in line with the key ideas of the collective homeostasis framework. Further analyses are needed to deepen our understanding of the emergent behavioural dynamics at the meso-scale level, particularly regarding how synchronisation tendencies manifest in different tactical contexts and structural configurations.

These spatial asymmetries may reflect general structural properties of football gameplay. Similar asymmetrical flow patterns were reported by Morishita et al. [40], who used vector calculus to analyse last-pass performance and demonstrated consistent lateral and directional asymmetries in elite level competition. Our findings provide empirical support for these observations by showing that certain simplices and synchronisation patterns tend to be concentrated in specific field zones, suggesting that these dynamics are not random, but likely represent stable, emergent features of collective system tactical organisation.

A deeper understanding of how players behave and coordinate in these cooperative and oppositional dynamics – specifically regarding movement synchronisation at the meso-level, could provide crucial insights into the regulatory processes governing team performance. Specifically, it could be relevant to understand how the interactions between players (as system components) and the adapter (responsible for adaptive collective behaviour) shape synchronisation tendencies and spatial-temporal coordination, ultimately influencing team organisation and performance.

5. Final Considerations

The findings revealed that the most frequent simplices were 1vs.1, 1vs.2, and 2vs.1, with both structure type and ball possession significantly influencing synchronisation dynamics. Simplice size also impacted synchronisation, as larger structures showed lower synchronisation tendencies. These dynamics reflect the collective homeostatic regulation that supports effective team synergy.

From a practical standpoint, these findings suggest that coaches and performance analysts should pay attention not only to tactical systems, but also to the variability and adaptability of player interactions. By analysing synchronisation tendencies, the type of simplice structures, and their specific locations on the field, coaches can gain valuable insights into how players interact under different competitive demands. This information can be used to design training tasks that manipulate the number and roles of players in various field zones, thereby enhancing the team’s adaptive capacity and promoting greater resilience and tactical flexibility during competition.

While the level of detail obtained through our analysis goes beyond what is typically observable in real time by coaches, it provides a foundation for developing data-informed tools to assist support practitioners in monitoring emergent coordination tendencies. In practical terms, insights from simplice structures and synchronisation dynamics could be operationalised into visual dashboards or automated reports by analysts and sport scientists that identify common relational patterns (e.g., frequent 2vs.1 situations in specific zones), detecting fluctuations in synchronisation across different phases of play. These tools could support post-match evaluations or, depending on technological development, near real-time decision-making. Although such fine-grained insights may not be captured by observation alone, the proposed framework opens avenues for integrating automated spatiotemporal analysis into applied performance contexts.

Beyond their applied value, these findings also have important implications for future research. The identification of consistent simplice patterns and their location-specific synchronisation tendencies may serve as useful markers of emergent regulation strategies, providing a theoretical basis for comparative studies across different teams, tactical formations, or levels of competition. Moreover, tracking how these patterns fluctuate across matches or throughout a season can help assess a team's adaptive capacity and regulatory stability over time—offering a functional perspective for performance monitoring and tactical evolution.

The collective homeostasis model proposed in this study draws conceptual inspiration from the study of biological systems, where system-level stability is achieved through distributed local regulatory processes. Similar to how biological systems regulate variables through continuous feedback and co-adaptation among subsystems, we conceptualise football teams as dynamic collectives whose behavioural organisation reflects ongoing attempts to maintain functional equilibrium in response to fluctuating performance demands. This theoretical grounding aligns with key ideas of the ecological dynamics framework, where perception-action couplings and affordance-regulated behaviour support the emergence of system-wide coordination patterns and tendencies.

The findings of this study are subject to certain limitations, particularly the sample size, which limit the generalization of the results. In addition, the study did not explore the relationship between synchronisation tendencies and specific performance outcomes (e.g., ball recoveries, goal-scoring opportunities), nor did it include contextual elements such as ball position data. Another limitation lies in the absence of detailed information regarding team characteristics – such as tactical systems, player characteristics and functional roles, and strategic plans – which may significantly influence synchronisation tendencies and homeostatic regulation. Furthermore, it is important to acknowledge that our synchronisation measures were based on static positional variables—distance and angle to the goal—which do not capture the full temporal dynamics of players' movements and interactions. This theoretical limitation means that the current approach may not fully reflect the continuous, dynamic coupling processes underlying emergent coordination in team sports. Future studies could benefit from integrating dynamic, movement-based synchronisation metrics, as proposed by Kijima et al. [41], Okumura et al. [42], and Mizawa et al. [43], which offer frameworks to analyse evolving coordination patterns in competitive contexts. Combining these dynamic measures with our simplex-based structural approach may provide a more comprehensive understanding of collective system behavioural tendencies and their regulation in sports teams.

To address these limitations, future studies should analyse a larger number of games across different teams, leagues, and competitive levels, incorporating contextual and performance-related variables. In particular, investigating how synchronisation tendencies relate to team performance outcomes – such as goal conversion rates, defensive recoveries, or attacking efficiency – could provide deeper insights into its impact on team performance. Examining a more extensive dataset would also enhance our understanding of how these adaptive processes evolve over time, supporting a team's growth. This expanded understanding of team dynamics in adaptation is essential, as it reflects the team's capacity to reorganize and adjust effectively, ultimately enabling players to perform at a higher level [44]. Such research will also aid in developing training programmes that help refine competitive transactions of players at the micro, meso, and macro levels, enhancing the team's collective capacity for synchronized, high-performance teamwork.

Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability statement

Raw output data from this research are available upon reasonable request to the corresponding author.

References

[1] P. Passos, D. Araújo, and A. Volossovitch, *Performance analysis in team sports*. Taylor & Francis, 2016.

[2] P. Silva *et al.*, *Practice effects on intra-team synergies in football teams*. 2016, pp. 39-51.

[3] L. Vilar, D. Araujo, K. Davids, and Y. Bar-Yam, "Science of winning soccer: Emergent pattern-forming dynamics in association football," *Journal of Systems Science and Complexity,* vol. 26, 2013, doi: 10.1007/s11424-013-2286-z.

[4] R. Santos, J. Ribeiro, K. Davids, and J. Garganta, "Sports teams as collective homeostatic systems: Exploiting self-organising tendencies in competition," *New Ideas in Psychology,* vol. 71, p. 101048, 2023, doi: https://doi.org/10.1016/j.newideapsych.2023.101048.

[5] R. Santos, J. Ribeiro, K. Davids, and J. Garganta, "Developing Performance in Sports Teams Through a Collective Homeostasis Model Supports Regulation, Adaptation, and Evolution in Competition," *Adaptive Behavior,* vol. 33, no. 2, pp. 151-162, 2025, doi: 10.1177/10597123241309980.

[6] J. Gibson, *The ecological approach to visual perception*. Boston: Houghton Miffin, 1979.

[7] M. A. López-Felip, T. J. Davis, T. D. Frank, and J. A. Dixon, "A cluster phase analysis for collective behavior in team sports," *Human Movement Science,* vol. 59, pp. 96-111, 2018, doi: https://doi.org/10.1016/j.humov.2018.03.013.

[8] L. Vilar, D. Araújo, B. Travassos, and K. Davids, "Coordination tendencies are shaped by attacker and defender interactions with the goal and the ball in futsal," *Human Movement Science,* vol. 33, pp. 14-24, 2014, doi: https://doi.org/10.1016/j.humov.2013.08.012.

[9] D. Araújo and K. Davids, "What Exactly is Acquired During Skill Acquisition?," *Journal of Consciousness Studies,* vol. 18, pp. 7-23, 2011.

[10] G. M. Edelman and J. A. Gally, "Degeneracy and complexity in biological systems," *Proceedings of the National Academy of Sciences,* vol. 98, no. 24, pp. 13763-13768, 2001, doi: doi:10.1073/pnas.231499798.

[11] L. Seifert, J. Komar, D. Araújo, and K. Davids, "Neurobiological degeneracy: A key property for functional adaptations of perception and action to constraints," *Neuroscience & Biobehavioral Reviews,* vol. 69, pp. 159-165, 2016, doi: https://doi.org/10.1016/j.neubiorev.2016.08.006.

[12] R. Duarte, D. Araujo, V. Correia, K. Davids, P. Marques, and M. Richardson, "Competing together: Assessing the dynamics of team-team and player-team synchrony in professional association football," *Human Movement Science,* vol. 32, pp. 555-66, 2013, doi: 10.1016/j.humov.2013.01.011.

[13] J. Ribeiro *et al.*, "A multilevel hypernetworks approach to capture meso-level synchronisation processes in football," *Journal of Sports Sciences,* 2019, doi: 10.1080/02640414.2019.1707399.

[14] T. Laakso, B. Travassos, J. Liukkonen, and K. Davids, "Field location and player roles as constraints on emergent 1-vs-1 interpersonal patterns of play in football," *Human Movement Science,* vol. 54, pp. 347-353, 2017, doi: https://doi.org/10.1016/j.humov.2017.06.008.

[15] T. Laakso, K. Davids, J. Liukkonen, and B. Travassos, "Interpersonal Dynamics in 2-vs-1 Contexts of Football: The Effects of Field Location and Player Roles," (in English), *Frontiers in Psychology,* vol. 10, 2019, doi: 10.3389/fpsyg.2019.01407.

[16] D. Carrilho, M. Santos Couceiro, J. Brito, P. Figueiredo, R. J. Lopes, and D. Araújo, "Using Optical Tracking System Data to Measure Team Synergic Behavior: Synchronization of Player-Ball-Goal Angles in a Football Match," *Sensors,* vol. 20, no. 17, p. 4990, 2020. [Online]. Available: https://www.mdpi.com/1424-8220/20/17/4990.

[17] J. Ramos, R. J. Lopes, P. Marques, and D. Araújo, "Hypernetworks Reveal Compound Variables That Capture Cooperative and Competitive Interactions in a Soccer Match," *Frontiers in Psychology,* vol. 8, p. 1379, 2017, doi: 10.3389/fpsyg.2017.01379.

[18] J. Ribeiro *et al.*, "A multilevel hypernetworks approach to capture properties of team synergies at higher complexity levels," *European Journal of Sport Science,* pp. 1-22, 2020, doi: 10.1080/17461391.2020.1718214.

[19] P. S. Bradley, S. William, W. Blake, O. Peter, B. Paul, and P. and Krustrup, "High-intensity running in English FA Premier League soccer matches," *Journal of Sports Sciences,* vol. 27, no. 2, pp. 159-168, 2009, doi: 10.1080/02640410802512775.

[20] D. S. Valter, A. Collins, B. McNeill, and C. and Marco, "Validation of Prozone ®: A new video-based performance analysis system," *International Journal of Performance Analysis in Sport,* vol. 6, no. 1, pp. 108-119, 2006, doi: 10.1080/24748668.2006.11868359.

[21] M. L. McHugh, "Interrater reliability: the kappa statistic," (in eng), *Biochem Med,* vol. 22, no. 3, pp. 276-82, 2012.

[22] E. Montbrió, J. Kurths, and B. Blasius, "Synchronization of two interacting populations of oscillators," *Physical Review E,* vol. 70, no. 5, p. 056125, 2004, doi: 10.1103/PhysRevE.70.056125.

[23] K. Okuda and Y. Kuramoto, "Mutual Entrainment between Populations of Coupled Oscillators," *Progress of Theoretical Physics,* vol. 86, no. 6, pp. 1159-1176, 1991, doi: 10.1143/ptp/86.6.1159.

[24] M. Varlet and M. J. Richardson, "Computation of continuous relative phase and modulation of frequency of human movement," (in eng), *J Biomech,* vol. 44, no. 6, pp. 1200-1204, 2011, doi: 10.1016/j.jbiomech.2011.02.001.

[25] E. J. G. Pitman, "Significance Tests Which May be Applied to Samples from Any Populations," *Supplement to the Journal of the Royal Statistical Society,* vol. 4, no. 1, pp. 119-130, 1937, doi: 10.2307/2984124.

[26] E. Brunner and U. Munzel, "The Nonparametric Behrens-Fisher Problem: Asymptotic Theory and a Small-Sample Approximation," *Biometrical Journal,* vol. 42, no. 1, pp. 17-25, 2000, doi: https://doi.org/10.1002/(SICI)1521-4036(200001)42:1<17::AID-BIMJ17>3.0.CO;2-U.

[27] J. D. Karch, "Psychologists Should Use Brunner-Munzel's Instead of Mann-Whitney's U Test as the Default Nonparametric Procedure," *Advances in Methods and Practices in Psychological Science,* vol. 4, no. 2, p. 2515245921999602, 2021, doi: 10.1177/2515245921999602.

[28] J. Ribeiro *et al.*, "The Role of Hypernetworks as a Multilevel Methodology for Modelling and Understanding Dynamics of Team Sports Performance," *Sports Medicine,* vol. 49, no. 9, pp. 1337-1344, 2019, doi: 10.1007/s40279-019-01104-x.

[29] P. Passos, D. Araújo, and K. Davids, "Competitiveness and the Process of Co-adaptation in Team Sport Performance," (in English), *Frontiers in Psychology,* vol. 7, no. 1562, 2016, doi: 10.3389/fpsyg.2016.01562.

[30] P. Passos *et al.*, "Interpersonal pattern dynamics and adaptive behavior in multiagent neurobiological systems: conceptual model and data," (in eng), *Journal of Motor Behavior,* vol. 41, no. 5, pp. 445-59, 2009, doi: 10.3200/35-08-061.

[31] J. Garganta, J. Guilherme, D. Barreira, J. Brito, and A. Rebelo, "Fundamentos e práticas para o ensino e treino do futebol," in *Jogos Desportivos Colectivos: Ensinar a jogar*, F. Tavares Ed. Porto: FADEUP, 2013, pp. 199-263.

[32] M. A. Riley, K. Shockley, and G. Van Orden, "Learning from the body about the mind," (in eng), *Topics in Cognitive Science,* vol. 4, no. 1, pp. 21-34, 2012, doi: 10.1111/j.1756-8765.2011.01163.x.

[33] P. Silva, J. Garganta, D. Araujo, K. Davids, and P. Aguiar, "Shared Knowledge or Shared Affordances? Insights from an Ecological Dynamics Approach to Team Coordination in Sports," *Sports Medicine,* vol. 43, no. 9, pp. 765-72, 2013, doi: 10.1007/s40279-013-0070-9.

[34] L. Seifert, D. Araújo, and K. Davids, "Understanding Skilled Adaptive Behavior," in *The Modern Legacy of Gibson's Affordances for the Sciences of Organisms*, M. Mangalam, A. Hajnal, and D. G. Kelty-Stephen Eds.: Routledge, 2024, pp. 271-290.

[35] C. Torrents and N. Balagué, "Dynamic Systems Theory and Sports Training," *Education, Physical Training and Sport,* vol. 1, pp. 72-82, 2006, doi: 10.33607/bjshs.v1i60.609.

[36] D. Araújo and K. Davids, "Team Synergies in Sport: Theory and Measures," *Frontiers in Psychology,* vol. 7, 2016, doi: 10.3389/fpsyg.2016.01449.

[37] P. Passos, K. Davids, and J. Y. Chow, *Interpersonal coordination and performance in social systems*. Routledge, 2016.

[38] R. Santos and P. Passos, "A Multi-Level Interdependent Hierarchy of Interpersonal Synergies in Team Sports: Theoretical Considerations," (in English), *Frontiers in Psychology,* vol. 12, 2021, doi: 10.3389/fpsyg.2021.746372.

[39] K. Davids, P. Glazier, D. Araujo, and R. Bartlett, "Movement systems as dynamical systems: the functional role of variability and its implications for sports medicine," *Sports Medicine (Auckland, N.Z.),* vol. 33, pp. 245-60, 2003.

[40] T. Morishita, Y. Aruga, M. Nakayama, A. Kijima, and H. Shima, "Tactical analysis of football games by vector calculus of last-pass performance," *Physica A: Statistical Mechanics and its Applications,* vol. 666, p. 130507, 2025, doi: 10.1016/j.physa.2025.130507.

[41] A. Kijima *et al.*, "Switching Dynamics in an Interpersonal Competition Brings about “Deadlock” Synchronization of Players," *PloS one,* vol. 7, no. 11, p. e47911, 2012, doi: 10.1371/journal.pone.0047911.

[42] M. Okumura, A. Kijima, K. Kadota, K. Yokoyama, H. Suzuki, and Y. Yamamoto, "A Critical Interpersonal Distance Switches between Two Coordination Modes in Kendo Matches," *PloS one,* vol. 7, no. 12, p. e51877, 2012, doi: 10.1371/journal.pone.0051877.

[43] T. Mizawa, M. Okumura, and A. Kijima, "Temporal and Spatial Structure of Collective Pass-Chaining Action Performed by Japanese Top-Level Field Hockey Players," (in English), *Frontiers in Sports and Active Living,* vol. Volume 4 - 2022, 2022, doi: 10.3389/fspor.2022.867743.

[44] Q. He, D. Araújo, K. Davids, Y. H. Kee, and J. Komar, "Functional adaptability in playing style: A key determinant of competitive football performance," *Adaptive Behavior,* vol. 0, no. 0, p. 10597123231178942, 2023, doi: 10.1177/10597123231178942.