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Football Teams as Collective Homeostatic Systems:

Implications for Research and Practice

Ricardo Jorge Correia Santos

Porto, 2025

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To Carla, Diana e Luís

"*A Família Feliz*"

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If it is true that the path is made by walking and that many of the directions we take throughout life are mainly tied to a certain complicity that each of us establishes with ourselves, it is equally true that, with the fellow travellers we meet along the way – and especially those who deliberately choose to walk beside us – a particularly deep connection is established. It is to them, above all, that I wish to express my sincere gratitude.

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Resumo

Na presente tese procura-se avançar com fundamentação teórica e prática, assim como com demonstrações empíricas, referentes à reconceptualização das equipas desportivas (recorrendo ao futebol como exemplo) enquanto sistemas homeostáticos coletivos. O modelo de homeostasia coletiva procura evidenciar como as equipas se podem auto-organizar continuadamente através de permanentes interações, para manterem o seu funcionamento e organização durante o desempenho competitivo. De acordo com este modelo, o desempenho da equipa é co-regulado à medida que os comportamentos coordenados emergem através da formação de sinergias entre os jogadores, para se adaptarem de forma eficiente e eficaz, de modo a satisfazerem as restrições dinâmicas emergentes de ambientes competitivos. Compreender a homeostasia coletiva na interpretação da dinâmica auto-organizadora das equipas desportivas facilita a identificação e análise das respostas comportamentais adaptativas das equipas, subgrupos de jogadores e de jogadores considerados individualmente. O modelo apresentado na presente tese foi inspirado no modelo biológico e é composto por quatro componentes, a saber: a) jogadores, b) ponto de regulação, c) identificador, e d) adaptador. Tendo em consideração a grande capacidade dos humanos para construir e adaptar nichos ecológicos, este trabalho explora a criação de contextos desportivos enriquecedores para o desenvolvimento de interações adaptativas jogador-ambiente. Trata-se de um modelo de adaptação que enfatiza a importância de se criar um nicho desportivo rico em oportunidades de ação partilhadas, que induza a coordenação da equipa através do desenvolvimento da homeostasia individual e coletiva nas diferentes subfases do desempenho competitivo. Tendo em conta a identificação de tais comportamentos homeostáticos, foi desenvolvida uma proposta metodológica que viabiliza a captura de tendências de sincronização que decorrem das relações de cooperação e oposição entre os jogadores (simplice), considerando o ângulo e a distância em relação à baliza. Os resultados mostraram uma sensibilidade maior deste procedimento, em comparação com o sistema de coordenadas tradicional. Os valores de sincronização foram semelhantes ao comparar as variáveis “longitudinal” e “distância”; no entanto, as diferenças revelaram-se significativamente mais pronunciadas quando consideradas as variáveis “lateral” e “ângulo”. A frequência dos padrões das relações de cooperação e oposição entre os jogadores durante o jogo, a influência da posse de bola e os efeitos do tamanho e do tipo dessas interações nas tendências de sincronização revelaram ser fatores cruciais para compreender como a homeostasia coletiva é regulada numa equipa. Essa informação permite identificar e intervir em pontos específicos que regulam o jogo. A perspetiva da homeostasia coletiva, assim como a nova proposta metodológica explicitada, podem revelar-se ferramentas promissoras na análise da performance desportiva, tendo igualmente um papel relevante na monitorização e no controlo do treino de jogadores e de equipas.

PALAVRAS-CHAVE: FUTEBOL, COMPORTAMENTO HOMEOSTÁTICO, ADAPTAÇÃO, ANÁLISE DA PERFORMANCE, DINÂMICA DA EQUIPA, TENDÊNCIAS DE SINCRONIZAÇÃO

Abstract

This thesis seeks to advance theoretical and practical foundations and empirical demonstrations regarding the reconceptualization of sports teams (using football as an example) as collective homeostatic systems. The collective homeostasis model aims to demonstrate how teams can continuously self-organize through ongoing interactions to maintain their functionality and organisation during competitive performance. According to this model, team performance is co-regulated as coordinated behaviours emerge through the formation of synergies among players, enabling them to adapt efficiently and effectively to satisfy the dynamic constraints of competitive environments. Understanding collective homeostasis in interpreting the self-organizing dynamics of sports teams facilitates identifying and analysing adaptive behavioural responses from teams, player subgroups, and individual players. The model presented in the thesis was inspired by the biological model and is composed of four components: a) players, b) set point, c) identifier, and d) adapter. Considering humans' strong capacity to build and adapt ecological niches, this thesis explores the creation of sports contexts that foster adaptive player-environment interactions. This model of adaptation emphasizes the importance of creating a sporting niche, rich in shared affordances, allowing for team coordination through the development of both individual and collective homeostasis in the different subphases of competitive performance. Considering the identification of such homeostatic behaviours, a methodological proposal was developed to capture synchronisation tendencies established by the relationships of cooperation and opposition between players (simplice), considering the angle and distance relative to the goal. The results demonstrated greater sensitivity compared to the traditional coordinate system. Synchronisation values were similar when comparing longitudinal and distance variables; however, differences became significantly more pronounced when constrained by lateral and angle variables. The frequency of patterns of relationships of cooperation and opposition between players during a game, the influence of ball possession, and effects of size and type of these interactions on synchronisation tendencies were all crucial to understanding how collective homeostasis is regulated within a team. This information enables the identification and intervention in specific points that regulate the game. The collective homeostasis perspective, along with this new methodological proposal, may prove to be a promising tool for analysing sports performance, and it also plays a significant role in monitoring and managing player and team training.

KEYWORDS: FOOTBALL, HOMEOSTATIC BEHAVIOUR, ADAPTATION, PERFORMANCE ANALYSIS, TEAM DYNAMICS, SYNCHRONISATION TENDENCIES

List of Abbreviations

GK – Goalkeeper

DEF – Defensive third

MID – Midfield third

ATT – Attacking third

RGT – Right side

LFT – Left side

dAG – Distance to attacked goal

dDG – Distance to defended goal

aAG – Angle to attacked goal

aDG – Angle to defended goal

dLong – Longitudinal displacements

dLat – Lateral displacements

Chapter 1

General Introduction

1.1 Introductory Note

"Sport is a stage where the representation of the body, its possibilities and limits, its dialogue and relationship with our inner and outer nature, with life and the world, takes place... it is an instrument for realizing a philosophy of the body and of life. It constitutes a hope for the need to live."

Jorge Olímpio Bento (2004)

Sport is undoubtedly a unique phenomenon with a profound impact on society, having evolved into a global sociocultural phenomenon in contemporary times (Lopes, 2007). It is an artifact par excellence created by our civilization to respond to the desire to establish the body as a platform for socialization based on principles and values that enhance both the individual and life (Bento, 2004).

It is difficult to remain indifferent to sports, whether due to the aesthetic beauty of each body movement or the fascination with individual or collective overcoming and transcendence. It is from collective cooperation, specifically in football teams, that our curiosity is stimulated in wanting to know certain phenomena associated with the performance and development of sports teams.

Football belongs to a group of sports known as collective sports games (Garganta, 1997) and shares a set of characteristics common to this group, such as: a) the constant confrontation between players of two teams, each understood as complex systems; b) the unpredictability and randomness of game situations; and c), the specificity of the game and the contextualization of motor skills within the specific system itself (Garganta, 2005). Regarding the first point, this confrontation requires cooperative actions among teammates and competitive actions against an opposing team to successfully achieve task goals (Castelo, 1994; Garganta, 1997). This is the essence of football as a game.

Football's current conceptualization and systematization describe it as structured around the concepts of attack, defence, and transitions. The perspective of the *offensive* and *defensive phase*s in an airtight manner, as if separated by cracks, in which attacking and defending have little or no contextual relationship, implies that those phases of the game are trained and understood in a separated and, sometimes, disconnected way, promoting a tremendous internal imbalance in teams (Teoldo et al., 2017; Teoldo et al., 2021). There is a general idea that a team with ball possession is attacking, and the opposing team is defending, and when there is a loss/recovery of the ball, the teams are in a transitional phase between both phases. This perspective displays a fragmented view of the game, in which the different moments are interpreted in isolation. This is a mutilating view of the game. On the other hand, the game of football is viewed as a continuous flow in which teams show both offensive and defensive behaviours simultaneously, and adaptive readiness is essential to respond to an increasingly demanding sport. Moreover, this is partly the richness of football, since it can be played, practiced, and thought of in plural (Teoldo et al., 2021).

At its highest competitive level, sport represents a radically human phenomenon that needs to be analysed and reflected within a specific context, shaped by its history, culture, time, and place of the observer. This contextual analysis reveals insights into our behaviours as human beings and highlights how understanding the biological organism can provide tools for continuous improvement in the sports dimension. In this sense, the homeostatic process, which has played and continues to play a crucial role in regulating life as we know it (Damásio, 2017), may contribute to a novel and enriching perspective on football. The question is: Could this biological principle contribute to an in-depth understanding of football, enhancing the preparation and performance of a sports team?

Building on this premise, this thesis proposes a new framework for interpreting competitive football performance. By doing so, it seeks to unravel new avenues for research and training in this sport.

1.2 Why Homeostasis?

"Homeostasis is the powerful innate imperative whose fulfilment implies, in every living organism… persisting and prevailing. The part of the homeostasis imperative that concerns persistence… leads to survival and is taken for granted without any specific reference or reverence whenever thinking about the evolution of any organism or species. The prevailing part of homeostasis... ensures that life is regulated not only within limits compatible with survival, but also conducive to flourishing, to a projection of that life into the future of an organism or a species."

António Damásio (2017)

Homeostasis is a fundamental principle in many fields of biology. However, it has also inspired work across other domains, including, for example, its implications in economics (Damásio & Damásio, 2016), architecture (Furtado, 2010), and computational engineering (Williams, 2006). This thesis explores a new approach to analysing team sports performance, also rooted in homeostasis. To better understand its broader applicability, we will begin by examining the origin of homeostasis.

At the end of the 19th century, the physiologist Claude Bernard proposed an initial conceptualisation of homeostasis. Bernard noted that living systems needed to maintain innumerable variables in their internal environment within certain thresholds and limits (Bernard, 1878). The integrity of the internal environment results from highly coordinated chemical processes, enabling water, nutrients, and oxygen needing to be present in living tissues in appropriate quantities. This functionality requires an organisation of behaviours essential for the organism to survive as an integrated whole.

Later, the concept of homeostasis was coined by the physiologist Walter Cannon (1929). He defined homeostasis as the set of self-regulatory phenomena that lead to the preservation of constancy regarding the properties and the composition of the internal environment of an organism. The popular concept of homeostasis evokes the ideas of *balance* and *constancy*, but what must be avoided, when dealing with life, is balance, because thermodynamically speaking, balance means zero thermal difference and death (Damásio, 2017). Constancy is also avoided, as it evokes a sense of stagnation.

The expression "homeo", Latinized from the Greek word "homio", means "similar to", defined by thinking of systems designed by nature, whose variables generally exhibit flexible ranges (e.g., hydration level, blood glucose, blood sodium, temperature, among others), contradicting the idea of fixed adjustment points (e.g., thermostats).

Every living organism depends on maintaining a complex set of interacting metabolic chemical reactions. From the simplest unicellular organisms to the most complex plants and animals, internal processes keep their conditions within tightly regulated and controlled limits to allow these reactions to proceed. Homeostatic processes act at the cell level, the tissue, and the organ, as well as at the level of the organism as a whole (McEwen & Wingfield, 2010). At every level of existence, homeostasis is a driving force toward balance and adaptation to changes (Marks, 2019). From this perspective, homeostasis is seen not as a purely biological property but as a process of dynamic self-regulation that shapes the behaviour of a system (Billman, 2020).

While homeostatic systems demonstrate stability, homeostasis implies more than just stability (Damásio, 2017). The existence of life, of whatever kind, is due to an endless sequence of victories (i.e., adaptive successes or advancements that enable survival and the maintenance of balance in the face of challenges), and the homeostatic regulation plays a fundamental role in this process. Homeostatic regulation had evolved not to promote general health or perfect equilibrium but to ensure survival in the face of imminent danger.

In the context of sports performance, the idea of “survival” refers to the ability of players and teams to adapt to dynamic and unpredictable situations in competition. Understanding this regulatory process and realizing its importance for the organism’s survival is fundamental, as it is the starting point for the proposal of collective homeostasis present in sports teams.

1.2.1 *Team Dynamics and Homeostasis: A Symbiotic Relationship*

In team ball sports, the overarching aim of a team is to score more goals/points than the other team, requiring an initiative to score (attacking) and to prevent the other team from scoring (defending). This distinction between attacking and defending is somewhat of an oversimplification because there are sports (e.g., football) where a team can be defending a lead when in possession of the ball, and a losing team without the ball may be pressurizing space or the opposition ball carrier to re-gain possession. It may be more accurate to consider each team’s offensive and defensive capacities (Mateus, 2005) or adopt an adaptive readiness perspective. In this view, no team is exclusively engaged in an offensive or defensive process but in a state of dynamic balance between the two. Regardless of perspective, a defining feature of team ball sports is the continuous flow of interactions between cooperating and competing players, with or without the ball, to achieve the performance goals of each team (Mateus, 2005).

Sports teams are often viewed as complex adaptive systems composed of interacting individuals who develop cooperative relations to achieve successful performance outcomes (Duarte et al., 2012; Passos et al., 2016). The most striking challenge for a sports team is maintaining integrity and identity (Garganta et al., 2013), i.e., some degree of consistency in achieving successful outcomes within a dynamic environment. Faced with this challenge, the idea of the homeostatic process emerges as a regulatory process that enables adaptive responses. Homeostatic systems combine an ability to maintain integrity over time with an incredible capacity for interactive behaviour.

The world of sports, particularly football, is a field where the dynamics of human interaction and the complexity of collective performance come together. Within this scenario, successful teams are not merely a collection of talented players but also reveal themselves as complex adaptive systems capable of sustaining a dynamic balance among constantly changing variables.

In this context, the hypothesis of collective homeostasis emerges as an organizational and regulatory principle. This idea transcends the simple aggregation of individual contributions (in their various dimensions) within a team, highlighting the collective's ability to self-regulate and adapt to varying situations during a game.

With this refined perspective on homeostasis, and considering that individual performances are deeply entwined with teams` tactical constraints (e.g., players` roles) (Altmann et al., 2021) and the quality of opposing teams (Lago-Peñas & Dellal, 2010), it becomes crucial to explore the performance-environment relationship as a relevant scale of analysis (Davids & Araújo, 2010). This perspective emphasizes the need to investigate the ecology of the performance context and the player, where performance is understood as an emergent property of the dynamic interplay between individuals, their teams, and the surrounding environment.

1.2.2 *From an Ecological Understanding of the Game to Collective Homeostasis*

In complex adaptive systems such as football teams, emergent behaviours and self-organisation under constraints play a crucial role in explaining how patterns of coordination and collective behaviours emerge (Davids et al., 2013). These behaviours aim to maintain homeostasis within the team. Self-organisation tendencies, emerging from both local-to-global and global-to-local processes (Ribeiro et al., 2019), enable players and teams to form new structures (patterns of collective/homeostatic behaviour). These structures, known as synergies or coordinative structures (Davids et al., 2006; Kelso, 1998), allow players to reduce the number of feasible interpersonal linkages used in task-specific circumstances (e.g., scoring a goal). This reduction facilitates effective communication during goal-directed behaviours (Passos et al., 2009; Riley et al., 2012).

Importantly, synergies are dynamic systems that evolve (Thelen & Smith, 1994), meaning they are not static but adapt and change according to the demands and circumstances of the competition. Within this context, an ecological approach suggests that human knowledge of the world is based upon recurrent processes of perception and actions (Araújo & Davids, 2011) during which affordances (i.e., opportunities for actions) (Gibson, 1979a) are perceived in the context of sports performance (Araújo et al., 2009).

Affordances are directly perceived in terms of what an organism can do with and in the environment, independent of the perceiver`s expectations or mental representations of specific performance solutions stored in memory (Gibson, 1966, 1979b; Oudejans et al., 1996). According to Reed (1996a), affordances are environmental resources or properties of objects that individuals can exploit. These resources in the environment have incurred selection pressures on individuals, leading to the development of specialized systems for detecting and responding to them. Affordances, therefore, represent opportunities within the environment accessible to specific groups that have evolved the ability to perceive them (Reed, 1996a). From this viewpoint, affordances are collective environmental features that exist independently of individuals, who later acquire the ability to perceive and use them. Thus, these collective affordances can be perceived by individuals trained to become perceptually attuned to them (Silva et al., 2013).

Sports teams, as dynamic systems, rely on continuous interactions between perception and action, shaped by the constraints of the environment (e.g., the playing area) and the social dynamics within the team. Successful teams can be seen as those most effectively perceiving and acting upon affordances presented by their environment and their opponents, adapting their strategies and actions to continuously changing constraints (Davids et al., 2008). To enhance performance and gain an advantage over opponents, teams must train players to identify and act upon shared affordances (Silva et al., 2013).

By associating these ideas with the need for sports teams to demonstrate an efficient response in their homeostatic regulation, we recognize the importance of shared affordances and the fundamental role of creating a collective system (team) identity. This collective identity enables individual players to develop coherent relationships with teammates and opponents, remaining aligned with the team`s overarching goals. In other words, these individual homeostatic processes are essential for the effective functioning of a team`s collective homeostasis.

By linking collective homeostasis to ecological dynamics, we can better understand how players and teams adapt and self-regulate in response to fluctuating constraints, such as tactical demands, opponent behaviour, and environmental pressures. This framework also highlights a crucial purpose within these dynamics: the drive to persist and prevail – to overcome the opposition.

The ecological perspective provides a holistic lens for analysing performance, emphasizing the interdependence between individual adaptations and the collective dynamics within the broader ecological system of the game. Consequently, examining the current state of performance analysis in sport becomes essential, mainly to understand which methodologies and instruments can be used to capture homeostatic behaviours.

1.3 Performance Analysis in Sport: Capturing Homeostatic Behaviours in Complex Systems

Performance analysis, a sub-discipline of Sport Science research (Borms, 2008), has gained significant importance among various stakeholders – including coaches, performance analysts, and technical staff – across all levels of performance, from youth to semi-professional and professional players (e.g., (Koudellis et al., 2024; Kunrath et al., 2024; Norton, 2024; Piechota et al., 2024; Sousa et al., 2024; van Hemert et al., 2024). Since the pioneering work of Evers and Fullerton (1910), which likely provided the first significant insights in this area, interest in performance analysis as a methodological approach to enhance players development and preparation in team sports has increased over the years (e.g., Sarmento et al. (2022)).

Modern approaches to performance analysis focus on evaluating individual performance while understanding the emergent collective behaviours that arise from player interactions. These behaviours are intrinsically linked to the concept of homeostasis, a state where teams maintain functional balance, through the efforts of individual system components (the players), despite the dynamic and competitive nature of the game. This balance is achieved through continuous individual and collective adaptations to internal and external constraints, reinforcing the need for a systemic approach to analysing team performance.

Recent research highlights the value of examining tactical behaviours to understand how individual and team-level synergetic behaviour emerge in various competitive contexts (Low et al., 2020). These interactions reflect the dynamic relationship between players and their environment, emphasizing the need for teams to regulate and adapt their behaviours to maintain collective functionality. As Araújo and Bourbousson (2016) stated, understanding how these behaviours emerge during player interactions remains a fundamental issue for performance analysis, particularly given the complex nature of football.

The game's evolution over the years has encompassed several aspects, yet it has consistently centered on solving tactical problems (Teoldo et al., 2021). According to Teoldo and colleagues (2021), the evolution of football can be divided into distinct periods, each marked by unique characteristics: a) the first period is defined by the emancipation and identification of football as a sport with its characteristics (the formalisation – creation and restructuring – of rules allowed the transition from a game with mainly individual expressions to a collective game); b) the second period is defined by the implementation and evolution of game systems and the emergence of players with great technical capacity who responded to tactical developments. The logic that supported the effort to resolve the tactical problems highlighted was the continuous attempt to balance power between attack and defense (noting that the most exciting were those that focused on offensive characteristics, supported by the technical superiority of their players); c) the third period arises from the recognition of the need to increase the dynamics of the game (fluidity and continuity of movements). Regardless of the more tactical-physical or tactical-technical styles, the consequence of this significant and permanent increase in dynamics was reflected in the constant reduction of space and time, conditioning the defensive and offensive game of teams and players (defending attempts to restrict more and better the space and time, which implies speed; attacking seeks to dilate space and time to decide better and act, whether at high intensity or using rhythmic variability to limit opponents' adaptations). These periods underscore the game’s dependence on collective adaptations to sustain performance, emphasizing the importance of homeostasis in navigating the evolving demands of football.

Garganta and colleagues (2013) state that the complexity inherent to the game is fundamentally due to four factors: a) the composition of the system and the multiplicity of interactions established by its elements; b) variability of the surrounding environment; c) behavioural unpredictability of the participants; d) relations of ambiguity between determinism and chance, patterns and randomness. Due to this inherent game complexity, players and teams must be able to find the most appropriate responses to the desired collective behaviours and objectives for the different phases and moments of the game.

Considering the complexity of a football game, any analysis of a team`s performance must consider its socio-cultural context, ensuring a balance between each player`s independence and their interdependence with teammates and opponents (Davis & Sumara, 2010). Achieving this balance is essential for the team’s homeostatic regulation, which involves continuous adjustments at both individual and collective levels to respond effectively to the dynamic constraints of the game.

Individual performances are influenced by the team`s tactical constraints (e.g., players’ roles, strategy, tactics, etc.) (Altmann et al., 2021) and the quality of the opposing teams (Lago et al., 2010), among other factors. These constraints serve as inputs for homeostatic processes, enabling players to adapt their behaviours to maintain stability and align with collective goals. Therefore, the collective performance of a high-level football team emerges from the complex interactions between players and the constraints of the competitive environment (Gréhaigne, 1992).

Recognizing that the game unfolds as a dynamic set of interactions and specific knowledge, it becomes clear that effective performance depends on the ability of teams to regulate behaviours homeostatically. This regulatory process enables teams to adapt to emergent demands while maintaining functional balance. From a systemic perspective, key characteristics such as self-organisation and the emergence of complex adaptive behaviours based on establishment of simple interactions (simplicity of complexity) become fundamental to understanding this regulation.

The chaotic nature of the game, arising from the randomness of some events, further emphasizes the importance of homeostatic regulation. These processes enable teams to manage unpredictability and maintain operational coherence under varying conditions (Davids et al., 2013). Additionally, the fractal organisation of player interactions facilitates the creation of regularities within the game's complexity, allowing teams to stabilize their performance and achieve their objectives (Guilherme, 2004).

To capture players` interactions on the field (synergistic properties), one can use positional data collected from football matches. Several team-based metrics, such as the stretch index (Bourbousson et al., 2010), convex-hull (Moura et al., 2012), and centroid (Frencken et al., 2011), are available to analyse how players cooperate to achieve a collective spatial-functional advantage. Additionally, passing networks have been employed to provide a comprehensive overview of player interactions (Passos et al., 2011; Ramos et al., 2018). Other studies (e.g., Pacheco et al., 2022; Ramos et al., 2017; Ribeiro et al., 2019; Ribeiro et al., 2020) proposed hypernetworks as a novel methodology for analysing player interactions within competitive contexts. Hypernetworks extend traditional network analysis by capturing multi-player interactions (Ribeiro et al., 2019). The increasing models of hypernetworks can provide novel and valuable insights regarding team communication, as such networks enable consideration of multiple kinds of n-ary relations established between players during competition (Ribeiro et al., 2019; Ribeiro et al., 2020). Based on this methodology, this thesis will focus on capturing the homeostatic behaviours of players and teams during competitive performance.

1.3.1 *Hypernetworks as a tool to capture homeostatic behaviours*

A significant advance of hypernetworks is their ability to model higher-order relationships across micro, meso, and macro levels. Unlike traditional network approaches, hypernetworks capture interactions involving multiple agents simultaneously, making them particularly effective in analysing the complex and dynamic interdependencies inherent in team sports. By integrating spatiotemporal data, hypernetworks account for dynamic and emergent interactions between attackers and defenders, providing valuable insights into group coordination and the collective adaptation (e.g., simplices aggregation/disaggregation) required to respond to competitive constraints (Ribeiro et al., 2019). This makes hypernetworks instrumental in operationally linking different properties of synergetic team behaviour, contributing to a coherent understanding of collective homeostatic behaviour.

Aligned with this approach is the evaluation of synchronisation, which has recently garnered attention for its effectiveness in capturing player interactions. Synchronisation tendencies, as highlighted by studies by Folgado et al. (2018), Carrilho et al. (2020), Corrêa et al. (2020), and Ribeiro et al. (2019), reflect how players coordinate their collective actions during sub-phases of play to achieve performance goals. These tendencies are deeply connected to homeostatic regulation, as synchronisation represents the balance between individual autonomy and collective alignment within the team. Effective synchronisation ensures that players dynamically adapt to the varying constraints of the game, supporting the stability and resilience of the team's performance under pressure.

Investigating the collective homeostasis model underscores the importance of understanding individual and collective behaviours in team performance analysis. At the micro-level, players interact with their nearest teammates (at a meso-level) through n-ary interpersonal relations, which hypernetworks can represent with precision. These interactions produce complex behaviours or synergetic patterns observable at the macro-level (Ribeiro et al., 2019). The patterns and their level of synchronisation reflect the underlying processes of microscopic homeostatic regulation, which directly impact the team's overall stability. By bridging these levels of analysis, hypernetworks offer a powerful tool for exploring how individual and collective adaptions interact to maintain the balance essential for optimal team performance.

1.4 Structure and Aims

The main aims of this thesis are: (i) propose a new perspective on team sports by conceptualizing sports teams (using football as an example) as collective homeostatic systems, (ii) explore and understand the advantages of enhancing team performance through the collective homeostasis model, and (iii), capture and analyse the homeostatic behaviours of players and teams through a new methodological proposal. From this methodological proposal it is intended to: a) analyse synchronisation tendencies using new performance variables, specifically players' distance and angle relative to the goal; b) compare synchronisation tendencies using traditional longitudinal and lateral displacement measures with those based on distance and angle to the goal, assessing potential differences in their informational value; c), verify whether synchronisation tendencies vary across different field zones; d) identify the most frequently occurring cooperative and opposing structures (simplices) during a game; e) examine whether synchronisation tendencies vary as a function of ball possession and simplice size, given their potential influence on synchronisation; and f), evaluate the synchronisation tendencies of the most frequently occurring simplices.

This thesis encloses a compilation of four original research articles published and/or under-review in peer-reviewed indexed journals:

1. Santos, R., Ribeiro, J., Davids, K., & Garganta, J. (2023). Sports teams as collective homeostatic systems: Exploiting self-organising tendencies in competition. *New Ideas in Psychology, 71,* 101048. https://doi.org/https://doi.org/10.1016/j.newideapsych.2023.101048

2. Santos, R., Ribeiro, J., Davids, K., & Garganta, J. (2025). Developing Performance in Sports Teams Through a Collective Homeostasis Model Supports Regulation, Adaptation, and Evolution in Competition. *Adaptive Behavior, 33(2), 151-162*. https://doi.org/10.1177/10597123241309980

3. Santos, R., Garganta, J., Lopes, R., Davids, K., & Ribeiro, J. (2025). Capturing meso-level synchronisation tendencies in elite football teams: A novel method for analysing collective organisation in performance. (Submitted to *Chaos, Solitons & Fractals*)

4. Santos, R., Garganta, J., Lopes, R., Davids, K., & Ribeiro, J. (2025). Capturing homeostatic behaviour in elite football teams: Synchronisation tendencies of cooperative and oppositional dynamics. (Under review in *Apunts Educación Física y Deportes*)

Additional works that are not included in the main structure of the thesis but result from the collective homeostasis model:

5. Santos, R., Ribeiro, J., Lopes, Rui J., & Garganta, J. (2023). Capturing meso-level synchronisation tendencies in elite football teams: the effects of angle and distance to the goal. International Congress of CIDESD

6. Santos, R., Ribeiro, J., Lopes, Rui J., & Garganta, J. (2023). Quantifying the frequency of simplices types in elite football teams according to pitch areas. International Congress of CIDESD

7. Ribeiro, J., Santos, R., Garganta, J., Barreira, D., Davids, K., Lopes, Rui J. (2024). Assessing individual attractors in elite football teams using GPS positional data. 14th World Congress of Performance Analysis of Sport

8. Santos, R., Ribeiro, J., Lacerda, T., & Garganta, J. (2024). O Sentido Estético nos Comportamentos Adaptativos das Equipas Desportivas: Da necessidade de mudança à beleza evolutiva do jogo. *Revista Brasileira de Educação Física e Esporte, 38*, e38223958. https://doi.org/10.11606/issn.1981-4690.2024e38223958

9. Santos, R., Ribeiro, J., & Garganta, J. (In press). Passado, Presente e Futuro: contributos do modelo de homeostasia coletiva para a compreensão dos comportamentos adaptativos de equipas desportivas nos três domínios do tempo que regem o jogo. *Athletica Revista de Filosofia do Desporto*

Chapter 2

Sports Teams as Collective Homeostatic Systems: Exploiting self-organising tendencies in competition[1]

RICARDO SANTOS, JOÃO RIBEIRO, KEITH DAVIDS, & JÚLIO GARGANTA

Abstract

This paper proposes theoretical insights on how sports teams, conceptualised as homeostatic regulatory systems, can continually self-organise their ongoing interactions to maintain team functioning and organization during competitive performance. In the model, team performance is co-regulated as coordinated behaviours emerge through synergy (re)formation between performers to adapt efficiently and effectively to satisfy emerging dynamical constraints of competitive environments. Understanding collective homeostasis in interpreting the self-organizing dynamics of sports teams facilitates the identification and analysis of adaptive behavioural responses of teams, sub-groups, and individual players. As a starting point, a biological model of collective homeostasis is composed of four critical components: a) players, b) set point, c) identifier, and d), adapter. Understanding the interrelated functions of model components is fundamental to designing effective training sessions and programmes for development of self-regulating team performance. In terms of performance analysis, identification and disruption of specific set points will provide insights for studying how to negotiate critical moments of competitive game play.

Keywords: Sports Teams; Homeostasis; Self-regulation; Communication; Coordination; Ecological Dynamics

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[1] Santos, R., Ribeiro, J., Davids, K., & Garganta, J. (2023). Sports teams as collective homeostatic systems: Exploiting self-organising tendencies in competition. New Ideas in Psychology, 71, 101048. https://doi.org/https://doi.org/10.1016/j.newideapsych.2023.101048

2.1 Introduction

Current conceptualization and systematic analysis of performance in team sports, like soccer, considers it to be structured around phases of attack, defence, and transitions. There is a general idea that a team with ball possession is attacking and without ball possession is defending. When there is loss/recovery of the ball, teams enter a transitional phase between these phases of play. This perspective provides a fragmented, reductionist view of performance, in which the different phases of play are interpreted separately in isolation. Here we consider competitive performance in soccer, from a player-environment scale of analysis, predicated on a *continuous flow* of interactions in which teams display offensive and defensive behaviours at the same time. This systems orientation views adaptive readiness as essential for interacting with the dynamics of a demanding performance environment.

Considering performance-related questions like these facilitates the contemporization of training tools and methodologies, to enhance the functionality of athletes and teams at a systemic level. Adopting an ecological *player-environment perspective* is significant for developing coherent models for analysing and understanding competitive performance in sport. Utilising a systems perspective, sports teams have been conceptualised as *complex adaptive systems* composed of integral components (i.e., the players) (Davids et al., 2013). System components interact within the performance environment in a dynamic, interdependent and functional manner, revealing emergent, self-organizing tendencies in behaviour to achieve task goals (Davids et al., 2015).

Understanding the nature of self-regulatory tendencies in complex adaptive systems (i.e., those sustaining the co-adaptive performance interactions of competing teams), is essential for developing methodologies for performance analysis. A potentially useful conceptualisation is the homeostatic regulation system, a model which has contributed so much to human development (Damásio, 2017). Here, we explore its potential merit in understanding how players, individually and in teams, can self-regulate collectively and adaptively within dynamic performance environments.

2.1.1 *The concept of homeostasis*

Homeostasis is a biological property for regulating the state of (bio)chemical and physical conditions maintained by all living organisms during ongoing interactions with the environment (Betts et al., 2017). Organisms that exhibit innovative and efficient homeostatic tendencies (i.e., adaptation to constraints – see Newell (1986), for detailed information on the constraints model) enhance their capacity to survive, as these systems can quickly adapt to perturbations that threaten system functioning. Importantly, the homeostatic self-regulatory system has played a fundamental role in understanding natural selection and, consequently, the evolution of living organisms (Damásio, 2017).

Homeostatic systems combine an ability to maintain integrity over time with a functional capacity for interactive adaptive behaviours. Like many other organic systems (e.g.,(Meyer et al., 2016; Weidenmüller et al., 2002), the collective homeostasis associated with sports teams captures the collaborative processes necessary to maintain the functional integrity of teams, supported by individual homeostasis (i.e., interactive, goal-directed behaviours of individual players for co-adapting within the performance environment (Mack et al., 2000).

In this opinion piece, we consider how a homeostatic regulation model could conceptually frame how players and teams continually (re)adjust their ongoing actions during competitive performance to dynamical constraints. These ideas on collective homeostasis underpinning self-regulation in team sports are well aligned with the key concepts in ecological dynamics (Passos et al., 2016). The proposed framework may provide novel insights for coaches, practitioners, and performance analysts regarding the design of training environments to enhance team organisation and functioning.

2.2 Conceptualizing Sports Teams as Collective Homeostatic Systems

Collective behaviours of sports teams are underpinned by homeostasis, with a purpose of self-regulation in order to maintain structural integrity within the parameters of *survival* in a sporting context. This specific understanding of 'survival' corresponds to effective behaviours adjusted to different contexts of competitive performance that emerge at different levels of complexity (i.e., from micro-meso-macro relations).

Considered at a micro scale of analysis (i.e., interactions between a player and a performance environment - which will have a great influence on other levels (e.g., micro-macro; player-team) due to the unique characteristics of each player), homeostasis allows an individual to adjust and refine their performance behaviours to the emergent contingencies of competition. System information in the form of specific values of interpersonal distances between competitors, speeds of approach and/or distance from teammates and opponents, need adjusting to maintain performance functionality (Duarte et al., 2010; Passos et al., 2008). These information sources support system self-organization tendencies that emerge between performers to exploit and (re)organise functional responses to emerging system perturbations in the environment, which can be internal or external in nature. Progressing to meso-scales of increasing complexity, in sectoral, intersectoral and collective terms, to perform successfully, players will have to effectively coordinate actions and behaviours (i.e., continually construct functional synergies) to avoid compromising a requisite level of collective functional organizational, which is continually under pressure from opponents. Thus, inherently adaptable properties underlying team organisation and functioning mirror those of collective homeostatic systems. The former emerges from the collaborative, synergistic processes developed by players to achieve performance goals during practice and competitive performance.

2.2.1 *The importance of collaboration in sport*

Collaborative processes are key for system functioning and adaptation, requiring teammates to coordinate goal-directed behaviours to deal efficiently and effectively with the dynamics of performance constraints in competitive environments. It has been argued that cooperation is indispensable to understand particular aspects of evolution (Nowak & Highfield, 2011; Nowak, 2006). Pursuing this line of thought, enhancement of collaborative behaviours can explain some changes in team performance. For example, competitive dynamics in soccer have adjusted towards increased teamwork and less individual performance behaviours over the last 30 years (Barreira et al., 2015). Hence, understanding collaboration has become increasingly important for understanding the functionality of the homeostatic nature of self-regulation tendencies in sports teams, particularly the implicit communication processes that continuously channel player interactions as system components.

Since collective homeostasis emerges from a group of autonomous individuals who form a sports team, the design of training programmes has tremendous importance in the development of the collective homeostatic system. The adjusted configuration of training sessions can provide necessary tools for enhancing self-regulation tendencies in teams, impacting on their organization and functioning. Understanding the events that lead to the emergence of different system states of order, disorder, and transitions between them, as adaptive behaviours (Araújo et al., 2013), is needed to identify the contexts in which the congruence between states of order/disorder is broken, shaping competitive outcomes (Ventura, 2013).

Conceptualizing sports teams as collective homeostatic systems might help to understand the evolutionary tendencies of teams, enriching our understanding of performance dynamics. Although the timescale of sport performance is not the timescale of evolution it is important to recognise that the same principles of homeostasis underpin the dynamics behind the necessary adaptations that emerge in sports organisations and evolving systems.

2.3 The Homeostatic Model

Homeostasis is a fundamental property of complex adaptive systems, to regulate environmental interactions, maintaining system stability and function through multiple dynamic balancing adjustments, adapting to perturbations through self-regulatory tendencies (Freedman, 2001).

Although self-organisation tendencies already have a biophysical theoretical explanation in Kelso's (1995) framework of coordination dynamics, the concept of homeostasis may provide a useful foundation for understanding how collaborative processes function for maintaining performance stability in a (collective) socio-biological system like a sports team. Indeed, homeostasis may provide a foundation for understanding how inherent self-organisation tendencies underpin functionality in athletes and sports teams conceptualised as dynamical systems (Davids et al., 1999).

In this paper, we refine a model proposed earlier (Modell et al., 2015) that reflects the function of homeostatic regulatory tendencies, including four critical components: a) **players**, as self-regulating agents who succeed by coupling perception and action; b) **set point**, a set of principles which guide a sports team's performance style, pertaining to a specific game model (which educates intentions of athletes); c) **identifier**, a set of aggregating ideas and intentions (related to the game model); d) **adapter**, that facilitates emergence of functional variability in systems within sport performance contexts.

These sub-systems function by perceiving a change or disturbance in a regulated (informational) variable with respect to bandwidth tolerances. A value of a key system variable, outside of the acceptable bandwidth, facilitates the search for a change in system behaviour to restore the regulated variable towards tolerance limits for its set point value (negative feedback systems).

2.3.1 *How the negative feedback system explains co-adaptive dynamics of sports teams*

One of the fundamental properties in a homeostatic regulatory system is the use of negative feedback to guide search for more functional solutions. This process provokes a mediating change in relation to a perceived system perturbation or disturbance which acts as information to guide re-organisation of system degrees of freedom (Bernstein, 1967) that seeks to address effects of a perturbation.

This model of self-organisation clarifies how a sports team can adjust its behaviours to satisfy different constraints emerging from the performance environment dynamics. In this way, a collective system can counteract perturbations and disturbances that might threaten the stability of its collective structure. In the same way that thermoregulation is a functional way of adapting body temperature in biological organisms, a sports team can regulate collective performance by teammates using surrounding information sources, for example by co-adapting distances between themselves.

This type of regulatory tendency in sports teams can help them to *survive* (defined as successfully competing in a sport context) by adapting to a dynamic performance environment. Indeed, a sports team can also evolve (defined as enhancing performance to compete successfully over a longer timescale) using these information-regulation processes to enhance actions. Another important point is that the homeostatic control system is dependent on and, in some instances, relies on delays in the system (see the work of Mackey & Glass (1977) in the modelling of physiological control systems). Time delays are an important constraint on team games performance in sports contexts. These constraints emerge at different scales of analysis and are exemplified at the scale of performance (perception and action immediately), in learning (days, weeks, months and years; players becoming more skilled and experienced) and development (months, years and decades; maturation and growth).

Again, training and practice in sport will help performers to adapt the homeostatic system of inter-personal regulation to the immediate delays of perception and action (where opponents use disguise and deception to prevent teams from understanding their intentions and tactical approach). Sometimes opponents surprise teams by playing a different formation or tactical system than that identified by performance analysis of previous performances. This can cause a delay as players work out how to adapt their own formation, often signifying a slight adaptation of roles for specific players in the group. Adaptations (resulting in synergy re-formations) between players in a team are, thus, an important part of competing successfully over the timescale of a whole season of games. Adaptive behaviours between players in a team have been revealed as an important component of competing successfully in high level competition (He et al., 2023).

Facing adversity in competition, a team needs to develop collaborative processes that strengthen the collective system's adaptive interactions in order to maintain system survival (maintain collective performance stability in sport contexts). An important aspect in this self-regulatory tendency is the need for a team to exploit division of labour (Eccles, 2010), in which players can take on different roles and tasks during competitive performance (e.g., in attack, a team with ball possession may have the majority of players focusing on creating defensive imbalances in opposition organisation to complete a scoring attempt). At the same time, other teammates are concerned with covering key spaces in case the ball is suddenly lost. In this way, a homeostatic conceptualisation of team organisation in phases of play avoids fractured and reductionist analyses of competitive performance because, while a team is attacking, some players may adopt a more defensive role to sustain momentum in attack if possession is conceded to counter the threat of a counterattack. For this reason, it may be better to analyse collective system performance in terms of agent roles (attacking or defending) rather than positions (attacker or defender) (Laakso et al., 2017).

Figure 1 illustrates this regulatory process, the ecological model of the homeostatic process in a sports team and its components.

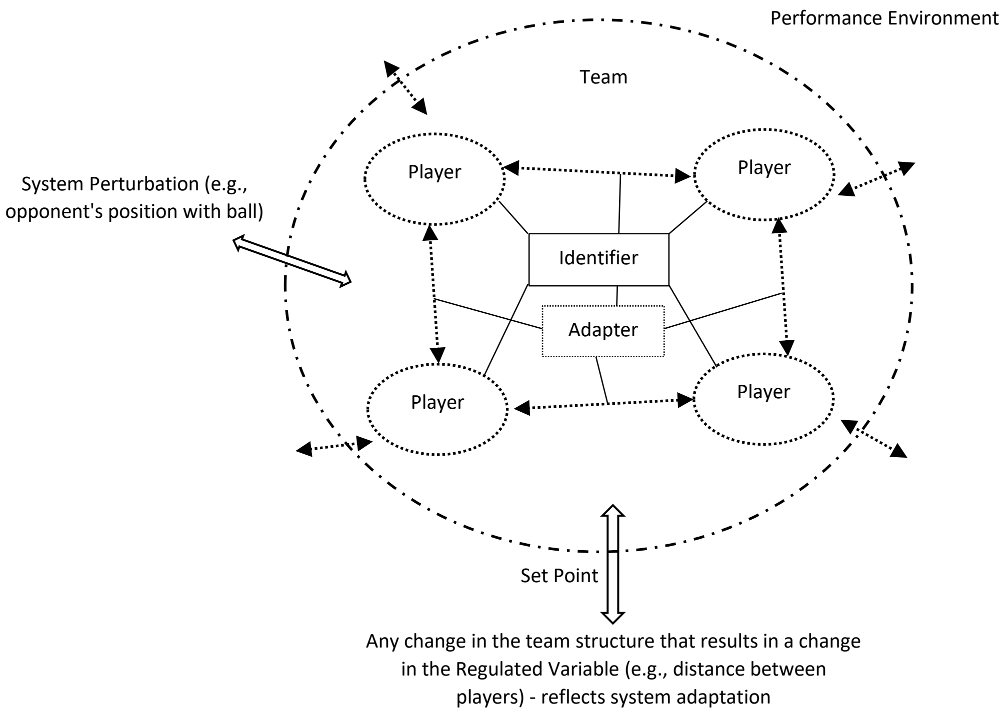

Fig.1. Homeostatic regulatory model in a sports team

2.3.2 *Players*

In this model, the players represent the highly attuned, information-seeking agents of the team through their continuous interactions, attending to perceiving and using key information sources for affordances in the surrounding environment (e.g., the location of the ball, the player in possession of it, available space). The player acts as a perception–action coupling agent in the team, in which each individual can perceive the value of key collective, performance-regulating variables (e.g., distance between teammates, interpersonal distances with immediate opponents) (Laakso et al., 2019; Passos et al., 2009). Individual actions contribute to shaping the dynamic values of key performance variables to maintain collective system stability. Each player can exploit system actions/behaviours harnessing the reciprocal compensatory system in the team (e.g., covering a gap left by a teammate). In coaching, from an ecological dynamics perspective, this idea aligns with processes of 'education of intention' (clarifying collective system performance goals) and 'education of attention' (individual performers becoming attuned to relevant information sources in their surrounding performance environment during practice to continuously monitor and regulate their goal-oriented actions) (Teques et al., 2017; Woods et al., 2019).

In the collective homeostatic system, team cooperation emerges from the continuous co-adaptation of all the players guided by surrounding information and framed by collective system intentionality (Passos & Davids, 2015). This is essential for sharing affordances (invitations for collective actions) and intentions (performance goals), and to reinforce that collective homeostasis is more than the sum of individual homeostasis (i.e., in each player), although collective system functioning is dependent on the unique contributions of each individual, since each player has singular characteristics (e.g., skill set, decision-making, experience, emotions, tactical knowledge) which are adjusted and integrated to enhance whole system functioning.

Importantly, collective system self-regulation is dependent on a degenerate (i.e., multiplicity of different performance solutions from the same components of the system (Edelman & Gally, 2001), self-organising, control system distributed amongst all players, predicated on adaptive homeostatic information regulation tendencies, regardless of individual components (e.g., when a player is injured and replaced, or a tactical substitution is made).

2.3.3 *Set Point*

In biophysical systems the set point corresponds to information of the intended values in a regulatory feedback sub-system, as in regulating temperature or pressure. In a sports team, the set point can be equated with key informational variables associated with tactical principles of play (e.g., at a moment of defensive transition, a team can pressure the opposition ball carrier and the surrounding space, with the objective of re-gaining possession, preventing long passes or assuming defensive organization for closing down space between defensive lines). In this example, the set point of the team can act as an informational variable at a specific moment in the game, facilitating a sudden change in organisational function (i.e., offensive to defensive) and a decrease in players` interpersonal distances values at the moment where ball possession is lost.

Importantly, while the homeostatic control model has its basis in negative feedback loops, which are local and relatively fast, allometric control in the system allows provides a basis for long-time memory (West, 2006, 2009; West & Griffin, 1998). It is important to mention that no technology provides a perfect model of human performance behaviours and needs some substantiation with some additional theoretical concepts. Here, system history or "memory" can be provided by a game model which encompasses the ecological concept of shared affordances ((Gibson, 1979a); in team games practice and performance, resulting in affordances **for** and **of** others – see Silva et al (2013)). Therefore, allometric control in the system can be substantiated by ensuring that affordances are designed into practice tasks so that an understanding emerges between players during the process of synergy formation within different sub-phases of play (attack, defence, transitions).

Designing performance landscapes in practice and training that are replete with shared affordances can support learners by using a homeostatic approach in team games performance through developing their knowledge of the environment to educate their intentions to support their interactions (Gibson, 1979a; Jacobs & Michaels, 2007; Silva et al., 2015).

2.3.4 *Identifier*

The identifier component corresponds to the capacity of the team, as an entity, to perceive and act upon information received through each player, for the shared affordances implied by the game model. In team sports there is a large variety of ways of approaching competitive performance and it's important that a group of athletes, typically from diverse background, have a clear understanding of how this specific squad of players is approaching competitive performance. The game model is conceived based on the specific performance philosophy of the coaching team and provide players with a certain 'performance identity'. The game model is commonly used in team sports preparation and comprises a set of guiding principles, captured as overarching intended performance outcomes, defined at different scales of complexity, and for different moments of the game (Guilherme, 2004).

In this way, the game model can frame the coherence and meaning for players and teams, substantiating a collective intentionality, influencing ways of thinking, perceiving, and acting in the performance environment. Importantly, a game model is not a mental model (which may contain *information about affordances* (Gibson, 1979a)), but is highly dependent on shared *information for affordances* (Gibson, 1979a) that sustains emergent interactions of team members with a performance environment. It is intended that players incorporate these principles, in the sense of truly feeling/living/experiencing them in the practice contexts that were created for them - "*reading cookbooks is not the same as cooking*" (Reed, 1996b, p. 108). This approach emphasises the importance of firmly establishing a "local to global" direction of synergy formation to harness in collective system performance (Ribeiro et al., 2019). Thus, the identifier component in the shared team control processes, distributed among all players, perceives the difference between indicative set point values and the actual values of an information variable that emerges during performance interactions (e.g., a team starts with clear performance intentions – shared intentions to seek affordances – to maintain ball possession to unbalance the opposition, seeking to circulate the ball to find, create and exploit gaps and open spaces in the opposition defensive structure).

2.3.5 *Adapter*

Like the identifier, the functioning of the adapter is predicated on self-organising tendencies in the team. The self-organising system adapter continuously receives information from the players, depending on the identifier of the team, promoting the search of a field of intended adaptive responses. The adapter initiates an appropriate team response to an *opportunity for (inter)action* emerging in an affordance field from a system perturbation highlighted by information from a regulated variable. This information source enhances the capacity of the team to perceive and act on available opportunities for action that can be utilised in performance. Moments of disturbance and perturbations are opportunities for interaction in which the team must act in order, for example, to reduce or increase the distance between sectors, thereby making the team more or less compact in a certain area of the field, depending on context. In this case, information on inter-sectoral space (weak area of the team that can be exploited by an opponent) can be perceived individually, or collectively (as intended) for the team to act on, based on this opportunity for interaction (to compact space or open up the field for an attack).

In order to provide appropriate responses, there is a need for shared affordances by the team (Silva et al., 2013), sustained by framed intentions, common goals and cooperative tendencies to achieve team success. These shared intentions enable the creation of specific information by acting in performance (Vaughan et al., 2021) that promotes skilled intentionality or effective coordination according to performance objectives. The ability to perceive information for affordances, and share the latter, is a performance tendency that emerges during practice, establishing skilled intentionality to enhance collective self-regulatory homeostatic tendencies.

2.3.6 *Regulated Variable*

A regulated variable is a collective system property needed to maintain system functionality, adjusted to the demands of 'competitive survival' in a sporting sense. Examples of a regulated variable include the interpersonal distance values between players in competition, players' fatigue levels, co-positioning of players according to essential informational references in the performance landscape (e.g., ball, line markings or scoring area). These specified information variables can be manipulated in training to promote the collective, homeostatic regulation of interactions between players and teams. Specified *information for* affordances enables emergence of effective homeostatic regulatory processes during competitive performance.

First, it is important to emphasize that, regardless of specific regulated performance variables, their analysis will always have to be undertaken according to the functional organisation of a specific team. Because each sports team has its own game approach, there are no recipes to be generalized to other teams. Even in analysing performance of a team, measurement of a regulated variable can provide different insights at different moments. Hence, a regulated variable should not be understood as a closed and rigid entity within an open system. In this respect, the set point can help coaches to analyse performance of their own team, based on what they observe and what is desirable or adjustable according to specific performance contexts.

Therefore, collective homeostasis should not be conceptualised as a measure that oscillates between values or limits that indicate whether a performance behaviour is correct or not. Rather, collective homeostasis, through efficient communication and coordination, provides a platform for adapting effective performance responses.

2.4 Conclusions and Practical Applications

In this paper, we discussed how the homeostatic regulation system could be used to explain the functioning of self-organisation tendencies in different sport performance contexts. Sports teams as collective homeostatic systems are characterised by multiple and interrelated individuals communicating and coordination between themselves in order to achieve shared intended performance goals. Understanding collective homeostasis in interpreting the organizational dynamics of sports teams may help identify and analyse the adaptive behavioural interactions of teams and players, within the guidelines that establish their identity. The term *interactions* is selectively significant here because the emphasis on person-environment interactions is a fundamental concept in an ecological dynamics interpretation of performance in sport. Interacting with a performance environment is different from merely *acting* (repeating and rehearsing techniques and set plays) and *reacting* (responding to sudden events in the environment). While the latter terms are sometimes important, *interacting* is essential in practice and performance since it involves sometimes seeking information to regulate actions, but also acting to create useful regulatory information (revealing available affordances).

Co-adaptive interpersonal regulation can be developed in training and practice, emphasizing use of available affordances **for** and **of** others and knowledge of the environment (Gibson, 1979a) to shape ongoing interactions. Practice in team sports should involve 'repetition without repetition' (Bernstein, 1967) to support the emergence of these co-adaptive behaviours at different timescales. The weaknesses found through the set point, whether they were failures of the team's own homeostatic regulatory system or imposed by the performance at one point in time by the opposing team, will enable the coaching staff to have a better understanding of this process and consequently act at the level of training preparation.

Homeostatic regulation allows team members to organise adaptive responses to performance dynamics in constant evolution. This may be facilitated by the training of sports teams to prepare them to attack and defend simultaneously, in order to maintain a balanced system state as long as possible in different game phases. Future research is needed to empirically elaborate on this homeostatic model by further analysing self-regulatory properties of sports teams during practice preparation and competitive performance.

Chapter 3

Developing performance in sports teams through a Collective Homeostasis Model supports regulation, adaptation, and evolution in competition[2]

RICARDO SANTOS, JOÃO RIBEIRO, KEITH DAVIDS, & JÚLIO GARGANTA

Abstract

The collective homeostasis model, grounded in ecological dynamics, has recently been proposed to explain the self-regulating individual-environment interactions that are necessary to conceptualising sports teams as collective homeostatic systems. Based on these insights and given the capacity of humans to construct and adapt their ecological niches, this article explores the creation of enriching sporting contexts for the development of adaptive player-environment interactions in competitive team sports. This model of adaptation emphasises the importance of creating a sports niche rich in shared affordances to enable team coordination through the development of individual and collective homeostasis in different sub-phases of competitive performance. In a homeostatic sports system, principles of play advocated by coaches allow players to intentionally coordinate and adapt their actions to shape the collective identity of the team. The team's identity is shaped by the synergetic development of collective attractors (stable system states) emerging at specific scales of complexity. This is facilitated through the manipulation of constraints by the coaching and support staff. These ideas have important implications for implementing team sports training and performance preparation, helping to transform the self-regulating tendencies of players through adapting their behaviours to dynamic performance contexts.

Keywords: Sports Teams; Individual Homeostasis; Collective Homeostasis Model; Performance Preparation; Ecological Niche, Skill Adaptation

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[2] Santos, R., Ribeiro, J., Davids, K., & Garganta, J. (2025). Developing Performance in Sports Teams Through a Collective Homeostasis Model Supports Regulation, Adaptation, and Evolution in Competition. *Adaptive Behavior, 33(2), 151-162*. https://doi.org/10.1177/10597123241309980

3.1 Introduction

In this paper we explore how understanding homeostatic processes in human behaviour (conceptualised as person-environment transactions) may contribute to a renewed perspective on adaptive performance in team games like football. Throughout this analysis we seek to illustrate that behaviours of individuals striving to enhance their functionality, through learning and performance development in a sports team, can be likened to a process of homeostatic adaptation. This idea has been captured as one of the main foundations in a new model of team game performance developed by Santos et al. (2023) termed *collective homeostasis*, which aligns with key principles of complexity science and dynamical systems theory. The utility of considering sports teams as homeostatic adaptive systems lies in how this modelling guides our investigation of player behaviours, in cooperating and competing, suggesting that the application of this perspective may influence the evolution of football as a cultural and social activity. Based on the fundamental principles of this contemporary model, and taking into account that homeostasis functions at all levels of biological systems, independent of scale (Torday, 2015a), we explore how these ideas may contribute to the development and performance of sports teams.

Here, we specifically examine the importance, for collective system (re)organisation, of the homeostatic process in biological systems, credited with a fundamental role in species development, including humans (Damásio, 2017). This analysis is based on the understanding that homeostasis should not be framed merely as a synchronic (real-time) servo-mechanism that maintains system status quo in organismic physiology, but rather as a dynamic process of system self-regulation in environmental transactions. As such homeostasis is an organising principle by which systems adapt their behaviours over different timescales (Torday, 2015b). The capacity of a system to adapt to a perturbation and maintain organism-environment homeostasis depends on the variety and quality of learned, functional responses it can develop and exploit.

To explore this concept, we will first discuss the connection between the functioning of sports teams and the collective homeostasis model in Section 2: *Sports Teams and the Collective Homeostasis Model*. In Section 3: *What Makes this Model so Enriching for Sport Teams' Performance?* we outline the reasons why the collective homeostasis model significantly enhances team performance. Section 4: *Components of the Homeostatic Model* examines how this model supports the development of its key components. Finally, in Section 5: *Can a Collective Homeostasis Model help to explain the evolution of game dynamics in team sports?* we offer insights into how this model elucidates the evolution of game dynamics in team sports.

3.2 Sports Teams and the Collective Homeostasis Model

Sports teams have been conceptualised as complex adaptive systems composed of different interacting components (individuals) which develop synergetic, cooperative relations, through practice and experience, to achieve successful performance outcomes (e.g., Davids et al (2013); Duarte et al (2012); Passos et al (2016). One of the biggest challenges for a sport team is the ability to maintain integrity and identity (Garganta et al., 2013), i.e., some degree of coherence in the way that they approach performance as a coordinated unit to achieve successful outcomes in a dynamic competitive environment. Players seek to use self-regulating tendencies, supporting them in satisfying the constraints of a competitive performance environment in sport, as captured in a model of *collective homeostasis* (Santos et al., 2023). In this insights paper, we show how this model is fundamental to develop and refine the adaptive responses of sports teams in solving problems linked to emergent context-dependent constraints of performance, during training and competition (e.g., the team must be prepared to attack and defend simultaneously).

Santos and colleagues (2023) highlighted that collective homeostasis mirrors the inherently adaptable process underlying organisation and function in team sports, which emerge from the cooperative, synergistic processes developed by players during practice and preparation for competition. This model consists of four components: a) **players**, as self-regulating agents who achieve intended performance goals by coupling perception and action systems; b) this intentionality in performance importantly acts as a **set point** or set of principles of play which guide or shape a sports team`s performance approach. Intentionality acts as a ‘specific control parameter’ to shape the order that emerges in a dynamical system (Kelso, 1995), pertaining to a specific performance model for a team (which educates the intentions of athletes); c) an **identifier**, that corresponds to a set of aggregating ideas and intentions shared by players (which frame the game model); d) the self-organising system **adapter**, which continuously receives information from the players, promoting the search of a field of intended adaptive responses. As illustrated in Figure 2, these sub-systems function by perceiving changes or disturbances in a regulated (informational) variable relative to boundaries of viability – that is, the team´s organizational references, which maintain balance and integrity. When a key system variable deviates from its set point and approaches its functional boundaries of viability, it prompts a search for adjustments in system behaviour to bring the regulated variable within its tolerance limits, closer towards the set point value.

The homeostatic regulatory model explains how adaptive behaviours in the collective system emerge from training to fine tune self-regulating tendencies underpinning team performance during transactions with the competitive performance environment, regulated by key information sources (Santos et al., 2023).

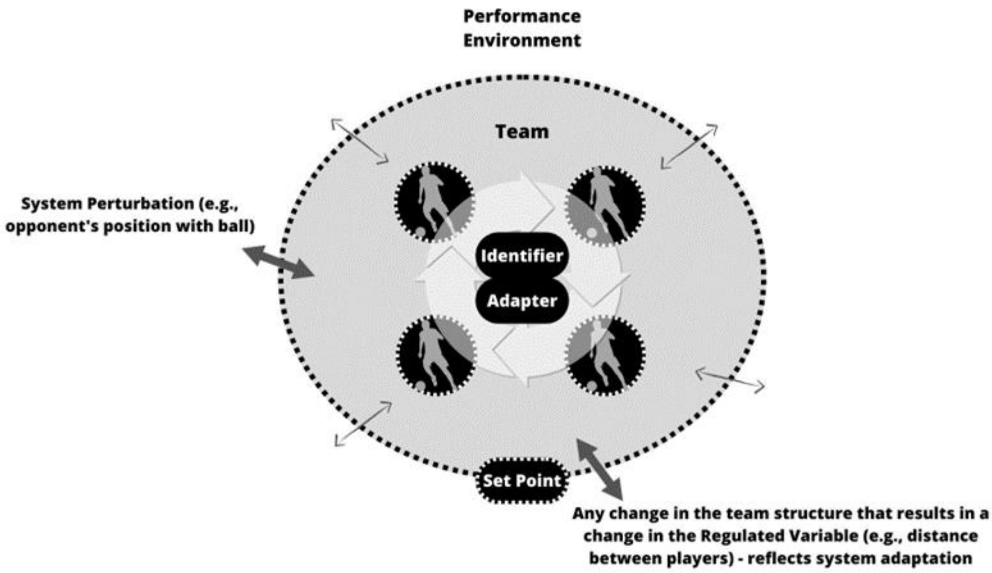

Figure 2. Homeostatic regulatory model in a sports team, adapted version from the collective homeostasis model by Santos et al. (2023)

3.2.1 *Collective system attractors shape team performance identity*

In team sports like football, performance (the ongoing coordination processes within individual players and between teammates and opponents) is a dynamical system (Davids et al., 2005). The development of a team's performance identity is based on the coherence of the collective system attractors, developed in training, i.e., collective, stable coordination tendencies towards which the behaviour of players and teams tend to converge more often under the specific constraints of competitive performance (Seifert et al., 2013). These collective system attractors (stable organisational tendencies) have a fundamental role, constantly shaping a team's coherence and identity, enabling the formation of a meaningful, shared understanding (attractor landscape) between all players in the squad. Establishing system attractors in practice supports the dynamic and self-regulatory homeostatic processes that can establish meaning and coherence for a team, helping it express its collective performance identity (e.g., tactical style, playing philosophy). In this way, collective system attractors have direct implications for the effective and efficient functioning of a team's homeostatic regulatory activities which need to be worked upon and developed in training and performance preparation. Indeed, the self-similarity nature of sports teams, considered as collective dynamical systems, implies that attractor properties may be observed to shape system tendencies at macroscopic and microscopic levels of analysis (Araújo et al., 2014).

More generally, humans have a capacity to act as niche constructors i.e., through their activities and choices they actively modify their own and each other's ecological environments, known as *niche specification* (Gibson, 1979a). Gibson (1979a) proposed that biological organisms inhabit and design eco-niches which contain relevant affordances (opportunities for action) available to guide their interactive behaviours with the environment. Exploiting these adaptive tendencies, the development of efficient homeostatic regulatory processes in sports teams may be predicated on sport practitioners developing an eco-niche in training and performance preparation. Indeed, Rothwell and colleagues (2021) invoked the concept of an eco-niche aligned with an ecological view of learning and development in sport organisations. They argued that successful team performers become skilled at perceiving surrounding information (e.g., events in the performance environment, the location of a scoring area to attack or defend, distances and gaps between teammates and opponents, and timing of player movements with respect to the ball) to guide their interactions with a performance environment. Thus, an initial stage in developing a homeostatic regulatory model to underpin team performance could be founded on developing an eco-niche in training to help players to express their agency on the field, by using available affordances, and ignoring others, in a performance landscape.

These key ideas have important implications for team sports players seeking to coordinate their actions together to achieve performance goals consistently during competition. Based on an understanding of the interrelated functioning of the components of this model, a set of ideas and perspectives, applicable in training, is presented to illustrate how a niche may be constructed in team development and performance preparation. This modelling approach can be implemented to effectively harness and exploit the self-regulation tendencies that emerge in sports teams, conceptualised as complex adaptive systems (Davids, 2015).

The proposed approach may provide novel insights for coaches, practitioners, and performance analysts regarding the design of training environments to enhance team organisation and functioning during competitive performance.

3.3 What Makes this Model so Enriching for Sport Teams' Performance?

In neurobiology, the homeostatic mechanism is a macro-system priority for maintaining the longevity, health and adaptive functionality of an organism (in sports contexts, this refers to the athlete and the team). However, this priority is dependent on the effective and efficient interactive functioning of other sub-systems operating at different scales of complexity (micro-meso-macro). Conceptualised as adaptive organisms, sports teams aim to compete successfully in their *sports battles* (winning in a competitive environment). Their regulatory process, crucial for evolving into a successful competitive entity, depends on micro-level homeostasis aligned with the overarching principle of collective homeostasis.

3.3.1 *Micro-homeostasis: A reality in team sports performance*

A system exhibits homeostasis at many different scales of analysis in maintaining the relationship between function and performance. In dynamical movement systems, homeostatic fluctuations at different levels of the system have a role in achieving the adaptive re-organisation needed to achieve a successful performance outcomes in a consistent way, exploiting inherent system degeneracy (Araújo & Davids, 2011; Santos et al., 2023). The 'interaction-driven architecture' (Bell et al., 2019) has been formally proposed as part of a theoretical explanation for how coordination and coordination variability can produce consistent performance outcomes in movement systems. These ideas are also important for understanding how homeostasis underpins dexterous movement coordination in athletes (micro homeostasis) and functional coordination between agents in a collective movement system (macro homeostasis) in striving for a team performance goal.

Micro homeostasis consists of individualised homeostasis effects that allow each player, individually, to co-adapt their behaviours with others during team performance e.g., modifying (reducing or increasing) values of key information variables that help regulate interactions with a performance environment. These informational constraints include values of interpersonal distances, approach velocities in co-adaptive movements of teammates and opponents, and available space in pressure zones. A football team in *ball possession*, framed by the key intention of attacking the opposition goal, can adopt systems of surveillance of space availability and movements of opposing players, in order to be prepared for a transitionary moment of ball loss. Consequently, micro homeostasis in this case is dependent on players' individual psychological (e.g., attentional, perceptual, decision making), technical (ball-recovery skills) and physical (e.g., speed of foot movement, agility, and power) characteristics, varying according to specific positions and player roles, predicated on self-regulation and co-interactive behaviours.

Indeed, the ability to augment performance by enriching interrelations between individual players and the team depends on an in-depth understanding of the homeostatic regulation of players and the team as a complex, adaptive system. Although important, one must not look to the aggregated sum of each player's functionality. Rather the emphasis in practice is on how players may synergise their individual homeostatic processes in co-adapting and exploiting system self-organising tendencies, when seeking to accomplish a collective task goal. The 'interaction-driven architecture' (Bell et al., 2019) of complex adaptive systems facilitates changes in individual system components (i.e., co-adapting players) to shape the way that performance outcome goals are achieved by exploiting the collective coherence of the homeostatic process in the team. Coherence and integrity of performance can emerge in a sports team through good coaching and insightful practice to support goal-directed collaborations emerging between players. These interactions can support the integration of their actions in close-knit, networked relations throughout performance that facilitates the spread of localised system fluctuations intended to influence the state of the global system (the competitive game). The constant transitions between stability and perturbation emerging from performance interactions of players can be soaked up by the global system organisation, when satisfying constraints imposed by minor local perturbations. Effects of tactical performance changes or individual contributions can develop stronger localised perturbations, leading to the emergence of new global system states of organisation (e.g., a levelling up of a game being lost) (Davids et al., 2005). This is a crucial point of the concept of collective homeostasis. The system is not destabilized by the transitions between stability and perturbation. Instead, the global organization can absorb and process these fluctuations. This is possible because the system, as a whole, is both resilient and adaptable. Collective homeostasis, therefore, is not about maintaining a static state of balance, but rather about the system`s ability to flexibly respond to disruptions arising from the interactions between its members and changes in the environment, allowing it to remain functional and coherent.

Exemplifying in football, some players may be coached to act as ‘enablers’, with their role (e.g., providing defensive balance and cover, occupying certain zones of the field when attacking) freeing up other players to express their skills in attacking areas of the field. These focused and limited performance behaviours are imbued with coordinative meaning, allowing the most creative players in the team to operate with more freedom. This freedom may allow them to exhibit exceptional technical skills and vision, passing ability, and dribbling skills to create goal-scoring opportunities in more advanced areas of the field nearer the opposition goal.

This systemic conceptualisation captures the bi-directional self-organisation processes underpinning synergy formation and the soft-assembly of different adaptive performance responses to challenges and problems faced in performance (Ribeiro et al., 2019). Training should simulate the game`s challenges, helping football teams develop the ability to use their “interaction driven architecture” to adapt and perform in real game situations. Practice designs that emphasise ‘repetition without repetition’ (i.e., performing the same task in varied ways to adapt to different conditions, emphasizing flexibility and learning rather than mechanical repetition) (Bernstein, 1967) will contribute to the team's evolution as a collective system and its continued integration and development. These types of challenging practice designs provide enriched opportunities for preparation of performance dynamics (see Otte et al., (2021), which implies shaping a sports niche for specifically developing individual and collective homeostatic regulatory systems. Next, we discuss how these homeostatic processes can be developed through the creation of an ecological niche.

3.3.2 Developing homeostatic processes through an ecological niche: self-similarity

When the environment or an individual athlete changes over time, there is an opportunity for behaviours that underpin their interactions to change as well. When the environment or an individual remains too stable (e.g., in a ‘comfort zone’ where the performance constraints are not varied enough or an individual is not challenged to adapt their actions, merely rehearsing techniques and tactical plans in practice), exploratory behaviours tend to be limited, decreasing opportunities for the emergence of novel synergies between players (Torrents et al., 2020). In essence, perturbations to the interactive performance dynamics of players in practice are needed to induce fluctuations in the athlete-environment system.

In order to enhance athlete or team functionality, coaches should seek to (re)design an ecological niche as a starting point when tasked with supporting development of specific athlete behaviours that could underpin performance excellence during competition (Rothwell et al., 2021). Insights on this practical challenge can be enhanced by understanding of self-similarity in complex, dynamical systems (Mandelbrot, 1967). Exploring self-similarity of a complex system and its components can reveal how the structure and function of a whole system (sports team) can be understood by analysing the structure and function of its parts (interacting players), providing rich insights for training and team performance preparation models (Davids et al., 2005).

In the context of football, the fragmentation of the game (Figure 3a) into smaller components while maintaining the essence of the whole (i.e., the full-sided game that is played and taught) is essential, as it preserves flows of specifying information or shared affordances (performance opportunities available in stable, collective system attractors) that regulate individual and collective homeostatic processes. Here, manipulation of task complexity and difficulty in performance scenarios during representative practice helps develop principles of play in a model scaled to specific phases of the full-sided game (Figure 3b).

These sub-phases of play need to be based on micro-components of the full game. They are exemplified in 3vs1 *[(1+GK) X (GK+1)+2]*, 2vs1 *[2 X (1+GK)]* or 3vs2 *[3 X (2+GK)]* scenarios (depicted in Figure 2b), showing self-similarity with the full-sided game. They encapsulate the complex micro-macro relationships, or principles of play, present in the full sided 11vs11 game of soccer. Guilherme (2004) argued that organizing learning tasks from this perspective, emphasizing the self-similarity inherent in such fragmentation, is a key methodological consideration in coaching, as it allows for more effective pedagogical interventions. This method of decomposing the game into its functional structures compels players to make constant decisions and solve problems, reinforcing principles of play across different game phases and periods, which collectively shape a specific game matrix (Guilherme, 2004).

From a scientific and technical perspective, it is important to distinguish between *complexity* and *difficulty* (see Garganta et al. (2013). Complexity refers to both the quality of interactions and the number of system components engaged in performance. For example, in sports teams, complexity can be reflected in the number of players available to support relational transactions (i.e., coordinated, collaborative actions during competitive performance. Garganta et al. (2013) argue that a less complex game (involving fewer players) may still be more challenging (with higher levels of task difficulty) because it places greater emphasis on the proficiency of technical actions. Consequently, players with technical deficiencies and limited game understanding may struggle to succeed.

To clarify this distinction, Figure 3b illustrates three pedagogical progressions that can be considered when developing the principles of offensive phase, specifically *penetration* (e.g., create advantageous conditions for the attack in numerical and spatial terms) and *offensive coverage* (e.g., supporting the ball carrier) during the attacking phase. For more detailed information regarding principles of play see Costa et al. (2015).

A pedagogical question that might capture readers' attention is: why start practice with a 3vs.1 (more complex due to the number of players involved) instead of a 2vs.1 activity? The problem is that, although less complex in terms of number of players involved, the 2vs.1 as a game format is highly dependent on the proficiency of technical skills from participating players. These include ball mastery skills such as good close ball control and manipulation skills, as well as enhanced dribbling and passing skills. Indeed, the two attacking players need to coordinate their tactical-technical skills under the pressure of a single defender. Furthermore, the ball carrier has only one player providing support (there is no triangular setup, which makes the play more predictable, because there are fewer affordances available) and less difficult for the defender than the 3-attacker interactions (which have more affordances available for the attacking unit). Essentially, the ball carrier needs to understand when to move the ball up field through dribbling, or to attract the defender towards them before passing the ball to their teammate and provide support. Alternatively, the 3vs.1 has a 3-player triangular setup which favors the attacking team, as there are 2 "free" players – who have more time and space, providing more affordances, while the ball carrier penetrates space around the lone defender and tries to advance with the ball up field.

Figure 3c shows the allometric control in the system (long-time "memory") substantiated by shared affordances 'for' and 'of' other players, underlying the accomplishment of principles of play (guide players' attention towards more effective actions and performance outcomes) in the game model emerging from individual and collective homeostatic processes. In collective homeostasis, each player is not just a passive agent but an active contributor to the regulation of the system. Individual actions directly influence the group`s overall state. In other words, individual homeostasis, aligned with the team`s allometric control, developed through both players and the team, allows for the regulation of the homeostatic process while also enhancing the team`s adaptive capacity.

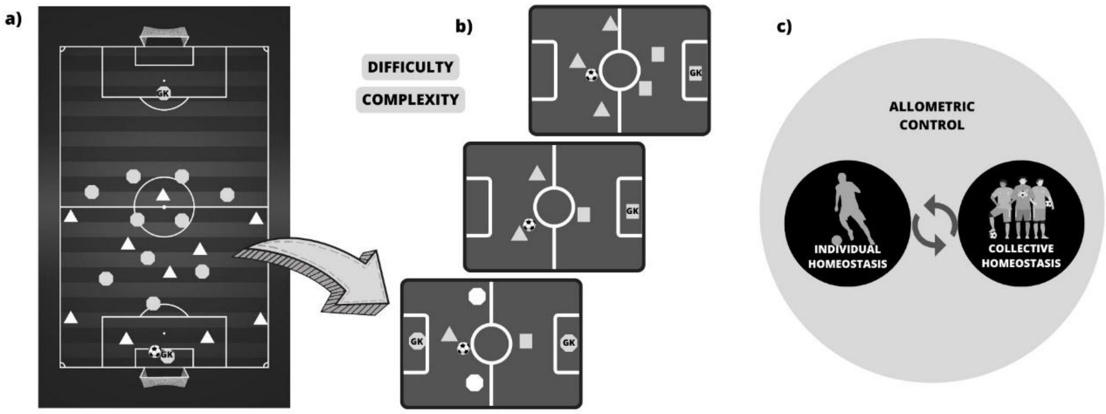

*Figure **3.** Illustration of a sports niche: **3a**: fragmentation of the game with representation of the whole; **3b**: managing task complexity and difficulty in specific game formats (e.g., 3vs.1 [(1+GK) X (GK+1) +2]; 2vs.1 [2 X (1+GK)]; 3vs.2 [3 X (2+GK)]) to develop principles of play; **3c**: regulation and adaptation of individual and collective homeostasis through allometric control.*

So, these practice design manipulations are characterised by different affordance landscapes and may also have implications for self-regulated learning and consequent development of individual and collective homeostasis. Therefore, three fundamental points must be considered: a) the individual (coach and each player) can promote significant changes in environmental conditions (they both act as 'niche constructors' (Rothwell et al., 2021); b) such modifications in practice design can tune players' intentions and attention, acting as selection pressures (i.e., help them perceive relevant information and utilise shared affordances to achieve intended performance outcomes); c) evolutionary responses (at the level of the homeostatic regulatory process – emerging at different system levels – from individual to collective) can induce such contextual changes.

In sum, combined with the perspective that collective homeostasis provides on self-regulating performance dynamics in sports teams, team sports training can provide an ideal stage for the transformative process of "*Homo Sportivus*" (Bento, 2007), supporting the production and reproduction of a collective identity. In the next section, we consider the development of each component of the homeostatic model.

3.4 Components of the Homeostatic Model

3.4.1 Players – "Unity and Collective Identity"

In the model of Santos et al. (2023), players represent a group of highly attuned, information-seeking agents within a team, continuously interacting and playing a decisive role in: (i) creating information through movements and performance actions that influence the behaviour of teammates and opponents, and (ii), shaping the dynamic values of key performance variables to help collective systems transition through states of stability, instability and metastability (i.e., a state in which a system remains stable for a period of time but is not in its most stable state) in their intrinsic dynamics (organisational tendencies) (Kelso, 2022). So, players develop the capacity to produce novel information based on the multiple ways they interact with the performance landscape in terms of perceptions, previous experiences, knowledge of the performance environment, and current competencies and abilities. Each player could engage in adaptive, goal-oriented actions/behaviours shaped by the principle of *reciprocal-compensation* (i.e., if one player contributes more or less in his/her expected role, other team elements should adjust their contributions, so that task performance goals are still attained) in the team (Araújo & Davids, 2016).

This understanding underlines the relevance for creating a performance niche in practice, conducive to the development of skill adaptation in each player, to help them attune to information and utilise affordances available in the surrounding perceptual-motor landscape. For example, when coaching a football player to improve their position in a defensive line, practice designs could provide them with shared affordances that develop attunement to information to perceive and act upon – related to the location of the ball, the goal area, and their co-positioning with immediate teammates and opponents.

These sorts of training sessions must be dynamic and rich in opportunities for players to continually solve problems, make decisions and choices, perceive information to interact with the environment and coordinate their actions to (re)organise their performance behaviours.

Rather than merely rehearse a choreographed defensive formation, the implementation of a homeostatic model in practice should provide players with opportunities to exploit inherent tendencies for system degeneracy (Edelman & Gally, 2001) (i.e., achieve the same or different performance outcomes with different coordinated actions), continually (re)organising their adaptive actions, to cope with ever-changing performance constraints (Duarte et al., 2012). To achieve these collective system aims, every player needs to be supported in establishing and maintaining a homeostatic state throughout performance, which resonates with the homeostasis of the collective system. Collective system functioning is highly dependent on the unique contributions of each individual, since each player has singular characteristics (e.g., skill set, decision-making, experience levels, among others) which are adjusted and integrated to enhance whole system functioning.

A fundamental aspect of this, which must not be neglected for the proper functioning of this whole homeostatic process, concerns athlete self-regulation with the dynamics of the environment (e.g., Guignard et al. (2020). Applied to sport, the self-regulatory perspective raises the question of how each player can take more responsibility for the quality of their interactions with a performance environment, continually working to improve it. Self-regulated learning emphasizes the active role of the performer in the process of learning, through exploring, discovering and exploiting the performance environment to find available key information sources to guide goal-oriented behaviour (Carvalho & Araújo, 2022).

Thus, if a player is motivated toward a high level of learning and improvement and is encouraged during training sessions to self-regulate (i.e., recognizing that their attitudes, behaviours, and problems reflect their own choices), this ecological approach to practice design will increase the likelihood of performance improvement. So, the challenge is to match the opportunities and emphasis for self-regulation with respect to the environment provided in training, to the desire for self-direction exhibited by the players.

Player responsibility has been largely neglected in research on football, and yet it has a great influence on a range of behaviours, either individual or collective, related to training and team performance (Konter et al., 2019). This concern follows the same line of thought as the basic foundations of the homeostatic model and may be used as a unifying concept, since reliable functioning of individual homeostasis is essential for efficient and effective collective homeostasis.

In this way, this model considers training as a continuous, transformative-adaptive process, serving to fine-tune the performance of players as perception–action coupling agents functioning in a collective system. In this system, collective attractors play a prominent role in inducing stable states of organisation, preparing the system for performance uncertainties, and exploiting functional variability to facilitate adaptive responses to emerging environmental challenges (Duarte et al., 2012).

3.4.2 Identifier – "Homeo (Tactic) Regulation"

In the collective homeostatic model, the identifier component corresponds to the capacity of the team, as an entity, to perceive and act upon specified information received through each player and the dynamics of the performance environment. Essentially, players perceive information and utilise shared affordances that allow them to establish functional synergies coherent with accomplishing a set of tactical principles of play pertaining to a specific game model (Santos et al., 2023).

Neurobiological systems are 'open' in the sense of regulating their information-based transactions with an environment following fundamental rules (in biology "everything is regulated"; (Carroll, 2016). In this way, sports teams are constrained by a set of tactical principles, which provide a guiding regulatory matrix for the open, homeostatic mechanism. The performance behaviours of a sports team emerge from a dynamic interactive relationship between the information from the environment in which it exists (provided by the competitive performance context and the training sessions in which it participates) and the *internal* environment (framed by the players` specific intentions and interactions guided by principles and sub-principles of play). This relationship forms the 'interaction-driven architecture' (Bell et al., 2019) that supports continuous (co)adaptations within the environment, promoting the development of self-regulation capacity of players and teams. The regulatory laws of performance (tactical principles of play) underpinning players and teams` intended interactions form a powerful specific control parameter (Kelso, 1995) framing this adaptive process for the team as an open system.

Practice designs need to include specifying information (that which is available in performance environments) so that players can be attracted toward intended performance outcomes. These outcomes should consistently emerge across varying levels of complexity, from fundamental skills to more integrated and dynamic actions. This aspect is so important because: a) players create invariants in movement (by finding the collective system attractors we can identify the key performance features that coaches need to pay attention to); b) players and teams quickly transit between different states of functional stability in open, unpredictable, and dynamic environments. These insights align with key ideas of Bosch (2020) that "stability matters more than perfection"; c) the type and number of variables encompassing the dimensions of an environmental niche may vary from one team to another, i.e., teams differ in the properties used to assemble their collective system attractors – each team has its own idiosyncrasies; and d), less functional attractors can result in sub-optimal performance patterns, i.e., inconsistencies between a game model and its operationalization, or states of team organisation mismatched with the intrinsic dynamics (key performance tendencies, dispositions and characteristics of players in the squad) may create challenges in adapting player actions to a game model. The way a coaching team manipulates the key task constraints in practice will be a key determinant in developing adaptive performance behaviours, impacting the self-regulated functioning of the team as an open homeostatic system.

3.4.3 Adapter – "Collective Frequency"

The coaching team´s role (in the development of collective homeostasis) is not to rehearse specific techniques or choreograph tactical patterns that are controlled to the *nth degree* in endless repetitions during practice. Rather, is to help instill positive and sustainable adaptive habits in players that enable them to continually learn, grow, and develop (Connolly, 2017). Earlier we noted the importance of the available 'interaction-driven architecture' of players and teams in predisposing such complex systems to explore, discover and adapt actions. These inherent system tendencies require practice activities and tasks which are designed to support the exploitation of exploratory actions through practice characterised as 'repetition without repetition' (Bernstein, 1967). During this process, experiences emerge through players' exposure to rich and varied training contexts, which can cause collective system fluctuations and perturbations, soliciting synergetic adaptations of players. Coaches need to design practice task constraints, full of representative game challenges and problems that help these adaptations emerge and become configured in line with a team's collective identity. Only when a team develops a collective identity (grounded in well-defined, collective system principles, with stable attractors, and incorporated by all players) will it be possible to change behaviours that compromise the *core personality* of the team (Lobo, 2019). Collective identity provides a shared framework and sense of purpose, aligning individual actions with the team`s overall goals. When all players understand and commit to these common principles, they are better equipped to modify behaviours that may undermine the team`s cohesion or effectiveness without losing sight of the team`s core essence. Thus, the adapter component is essential for homeostatic regulation in the *(re)organisation* of constant adaptations.

The self-organising system adapter corresponds to a collective capacity distributed between all players in the team, a tendency through which they interact with the performance environment by continually receiving information from teammates and opponents, filtered by the identity of the team, framing a set of adaptive intention-driven responses (Santos et al., 2023). Like the identifier, the adapter component depends substantially on the team's self-organising, soft-assembly tendencies and synergy forming dispositions (Santos et al., 2023). Psychologically, the squad players need to adapt to this performance philosophy over time, supported by the adapter.

The adapter initiates the appropriate team (re)organisation for exploiting an *opportunity for (inter)action* resulting from a perturbation signalled by regulated performance variable values (captured in distances, spaces, gaps, directions, co-positioning, movements of players), enhancing the capacity players in the team to perceive and act upon available opportunities for action – affordances that can be utilised in performance environments (Gibson, 1979a). For example, in football, a team losing ball possession, provides an opportunity for players to immediately act on that loss, perhaps by increasing pressure on the opposition ball carrier and closing off spaces for passing lanes to teammates. These opportunities for adaptive responses must be coordinated to be exploited and efficient and effective, always commensurate with principles of play adopted in performance preparation. The key point is that there are no perfect homeostatic regulatory processes, and it is important to know how to deal with system error. Performance errors have been considered a natural part of the learning process in sport (Burton & Raedeke, 2008), and the correction of such errors in team sports is of central concern to coaches. In an ecological dynamics' rationale, the aim in learning is not to mechanistically reproduce an ideal movement technique in competitive performance, that has been rehearsed in practice. This theoretical perspective has clear implications for coaching in practice: 'errors' may be viewed as opportunities for continuous refinement and adaptation in (re)assembling system performance. Players need to be exposed to surrounding information (systemic and, less frequently, augmented) that is continuously available to adapt and (re)assemble their performance. It is important, therefore, to create learning contexts so that players develop a functional interpretation of performance feedback and learn to deal with this surrounding (and augmented) information constructively (Homsma et al., 2007). Players need to understand that the homeostatic regulatory process is likely to be put under pressure or fail at certain critical moments in competitive performance (and in training). But the challenge is not to allow individual homeostatic failures to affect the coherence and integrity of the entire team structure (collective homeostasis). Therefore, it is necessary to promote the willingness to take full ownership of one´s behaviour (expressed in the common mantra: 'no excuses'), and be open to seeking surrounding, and augmented information (from coaches and performance analysts) available in individual and collective settings within football practice (Konter et al., 2019).

To support their openness to relevant feedback information, it is also important for players to experience opportunities in practice that enhance their skills in attuning to relevant perceptual information to regulate their actions. Training is a vital tool to shape this tuning process (Teques et al., 2017), offering players the opportunity to continuously explore flexible solutions, in terms of understanding how and where to explore, so that they can exploit the collective attunement to shared affordances that support team coordination (McGuckian et al., 2017).

The search for new and better adaptive responses (e.g., constrained by specific strengths or weaknesses of the opposition on the day) takes us to the set point of this homeostatic model.

3.4.4 Set Point – "Measure the Functioning of the System"

In the collective homeostatic model, understanding of the set point is directly associated with tactical principles of play. These principles pertain to a game model that frames allometric control in team performance (Santos et al., 2023). Different set points (at different time scales) are available to the regulating system, providing flexibility to respond effectively to a large variety of performance demands and uncertainty. The emergent value of the set point and its adaptation is dependent on the self-regulating tendencies of a team, based on its performance identity and the system's history (Santos et al., 2023). The set point is crucial for assessing how well the system (i.e., the team) regulates itself, helping to determine whether any team variables need to be adjusted. For example, this might include changing team shape, such as switching from 1-4-4-2 to a 1-4-5-1 when defending the goal or modifying the pressure tactics used after losing ball possession. The latter can be more passive or more aggressive depending on the specificity of demands solicited by the current state of the game, the location on field, the characteristics of the opposition or the positioning of colleagues nearby and related to any past game action in a similar scenario.

Augmented information from performance analytics will provide systemic feedback to help the coaching team and sport science staff to continue developing and building the most adaptive learning environments. Once again, this process is predicated on parameters that confer the team's collective performance identity and the principles that guide the regulation of the players' performance behaviours. This process will be (or should be) the starting point for analysing and updating the functionality of team interactions via the homeostatic regulatory process.

3.5 Can a Collective Homeostasis Model help to explain the evolution of game dynamics in team sports?

As mentioned by Santos et al. (2023) the ‘survival’ of a sports team in competition depends on the maintenance of collective homeostasis in key variables. Sport teams (and their form of organisation) will *survive*, and even thrive, as long as they can accommodate system perturbations without losing homeostasis. This view of a sports team as a first-order homeostatic adaptative system implies a view of evolution as a second-order adaptive process acting on the parameters of the first-order regulator.

A sports team is a homeostatic system with organizational parameters constrained by its tactical principles of play. Its learning contexts in training may be seen as a part of the homeostatic (re)organisation. Given that niche construction has played an important role in human evolution (Antón et al., 2014; Kendal et al., 2011), in a similar way, changing selection pressures on tendencies for team coordination behaviours to emerge and stabilise, by manipulating task and environmental constraints, could help us to understand the evolution of behavioural dynamics in collective system performance, to identify self-regulation tendencies. The adjustment of these selection pressures on self-organisation tendencies through training provides a functional ‘chaos + feedback’ loop that allows continuous (inter)action opportunities to be created and/or dissolved due to context-dependent changes. In this case, changes in context-dependent constraints, promoted in training and that, consequently, change the information present in a practice task, contribute to the development of self-regulating adaptive responses.

3.6 Summary and Conclusions

Throughout this paper we have sought to illustrate that learning and development of performance in sports teams can be likened to a process of homeostatic adaptation. The utility of considering sports teams as homeostatic adaptive systems lies in the way it can guide our exploration of their behaviours. Where we observe constancy in the face of perturbation, we should look for regulation and homeostasis. Where we see homeostasis, we should look for homeostatic adaptation. Ascribing different parts of a sports team to different roles in the homeostatic adaptive system framework, can lead to a better understanding of team behaviours. In this sense, understanding the important process of adaptation and development can lead us to understand evolution (of teams and game dynamics in team sports) as a special case of homeostatic adaptation.

Some forms of system (re)organisation will be better at withstanding perturbations than others and will, therefore, survive for longer, as with certain ways of performing. If successful, these system states may persist for a prolonged period until they are challenged by more efficient and effective changes in performance, such as constraints imposed by changes in tactical structures of other teams or even through changes in competitions e.g., through new rules, events, technology and equipment. The evolutionary adaptation of teams in sport and their performance certainly contributes a lot to the evolutionary dynamics of competitive contexts, like football, as a global phenomenon.

This perspective adds a new dimension to our over-arching theme of homeostatic adaptation providing a fundamental principle of human performance behaviours, when viewed at all dimensions of the system. The consideration of evolutionary constraints on the dynamics of sports teams, as well as the game itself, as a result of homeostatic regulation and consequent adaptation is an innovative way of thinking. Focusing on the evolving nature of sports performance highlights the importance of team preparation, training, and athlete development. These processes are grounded in the interaction between the environment and the performer, requiring continuous micro-level adaptations (such as athlete learning and development). This 'interaction-driven architecture' approach forms the foundation of macro-level homeostasis in team preparation.

The conception of collective homeostasis, rather than being a doctrine of constancy, is fundamentally a doctrine of dynamics, adaptability and change. It is through interacting with constant adaptations (chaos + feedback) that the players' behaviours/ team dynamics may be aligned with evolution in competition. The contribution of the ideas and foundations of this model for the development of sports teams may help advance and refine a sports niche, rich in shared affordances that support performance preparation, skill adaptation and improvement of individual and collective homeostasis process. Understanding how each team player perceives the competitive environment and, especially, how they coordinate and interact together, will be fundamental to improve team performance as a collective homeostatic process. Future research, based on this theoretical modelling, needs to continue to refine our understanding of the individual and collective homeostatic processes at work in players and sports teams.

Chapter 4

Capturing meso-level synchronisation tendencies in elite football teams: A novel method for analysing collective organisation in performance[3]

RICARDO SANTOS, JÚLIO GARGANTA, RUI J. LOPES, KEITH DAVIDS, & JOÃO RIBEIRO

Abstract

This study explores the emergence of synchronisation tendencies in elite football teams, emphasizing how players coordinate their collective actions, in sub-phases of play, to achieve performance goals under various competitive constraints. Drawing on ecological dynamics, the study highlights the player-environment relationship, analysing how ecological variables, such as field position, goal targets, and locations of teammates and opponents, shape collective decision-making. A novel method, using a newly developed coordinate system for capturing meso-level synchronisation tendencies is introduced, defined by values of angle and distance of subgroups of players (simplices) to the goal. This approach, designed to capture the continuous adaptive needs of homeostatic regulation in performance, successfully observing and reporting synchronisation tendencies between players emerging at the meso-level scale. Results demonstrate that this system has greater sensitivity in detecting synchronisation tendencies between players, compared to traditional coordination analysis methods. The key performance variables, angle and distance to goal, are critical constraints on players synchronized behaviours during the attacking and defending sub-phases of play. This novel method for observing and reporting synchronisation tendencies can provide coaches with crucial information to effectively structure and monitor player transactions during performance and training sessions.

Keywords: Football teams; Meso-level synchronisation; Distance and Angle to goal; Collective homeostasis, Player transactions

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[3] Santos, R., Garganta, J., Lopes, R., Davids, K., & Ribeiro, J. (2025). Capturing meso-level synchronisation tendencies in elite football teams: A novel method for analysing collective organisation in performance (Submitted to *Chaos, Solitons & Fractals*).

4.1 Introduction

Synchronisation tendencies between players in team sports have drawn significant attention, driven by the growing interest in understanding how cooperation and coordination between team members emerge in performance (e.g., Carrilho et a., 2020; Corrêa et al., 2020; Folgado et al., 2018; Ribeiro et al., 2019). Investigating synchronisation tendencies in elite football is crucial, as it shows how players coordinate their actions to achieve common goals while adapting to constraints.

Grounded in an ecological dynamics framework, the decisions and actions of individual players are continually shaped by surrounding information sources, such as field markings, the laws of the game and the locations of teammates and opponents on the field (Davids et al., 2006). Information is used to regulate actions, particularly those related to available affordances (i.e., opportunities for action (Gibson, 1979a), which appear and disappear in the performance environment. For example, pitch areas, goal location, and the co-positioning of teammates and opponents – cooperative and oppositional relationships captured by simplices (Ribeiro et al., 2019) – are critical ecological variables in competitive football. These constraints shape players' behaviours and influence their synchronisation tendencies, ultimately affecting the team's collective dynamics. Among these ecological variables, the players' distance and angle relative to the goal have been identified as crucial factors influencing tactical decision-making and coordination patterns (e.g., Romero Clavijo et al., 2018; Vilar et al., 2014).

Synergetic behaviours in teams emerge at the micro (e.g., dyadic player relationships such as 1vs.1), meso (group dynamics such as 3vs.2), and macro (team interactions) levels. These levels align with the hierarchical organization of open systems (Corrêa et al., 2021), where each level represents a distinct layer of complexity that is interconnected yet governed by specific dynamics and constraints. The meso scale has been recognized as a key ecological level for understanding synergy-formation processes, particularly in solving competitive challenges (Ribeiro et al.,2019). However, despite its importance, meso-level analysis has received limited research attention (Sarmento et al., 2022), reinforcing the need to bridge this gap in the literature. A deeper understanding of this intermediate level is essential for linking individual player interactions to the collective organisation of the team.

During competitive performance, specific subgroups of players emerge dynamically in offensive and defensive sub-phases of play. These transient yet functionally important interactions serve as a bridge between the micro and macro levels, as players engage with their closest teammates to generate consistent patterns of performance behaviours (Ribeiro et al., 2019). Understanding these meso-level dynamics is essential for capturing how local player interactions contribute to team synergies (Ribeiro et al., 2019).

In this regard, sports teams have been modelled using the concept of *collective homeostasis* (Santos et al., 2023). This theoretical model consists of four fundamental components: i) **players**; ii) **set point**; iii) **identifier**; and iv) **adapter**. Among these, the present study focuses on players conceived as self-regulating agents and the adapter, which reflects the team's ability to generate adaptive responses through self-organising processes. The model suggests that sports teams possess a self-regulatory capacity, enabling them to adaptively respond to information emerging from various competitive constraints, thereby reinforcing the emergence of synergetic behaviours across different levels of complexity (micro-meso-macro levels) (Santos et al., 2023).

From this perspective, meso-scale behaviours exemplify collective homeostasis in action, offering insights into how adaptive behaviours at a smaller scale contribute to the structural stability of the team (Santos et al., 2023, 2024). One way to access such coordination dynamics is through the analysis of synchronisation tendencies, which capture how players move in relation to one another and to the team as a whole. Traditionally, synchronisation tendencies of longitudinal and lateral displacement measures on field have been assessed using separate measures based on team-team (e.g., (Duarte et al., 2013) and player-team (e.g., (Duarte et al., 2013). However, in a football game, players perform a variety of multidirectional displacements (Fitzpatrick et al., 2019), not limited to longitudinal and lateral displacements, and their positioning in relation to both goals can influence decision-making (Vilar et al., 2014).

Seeking to investigate synergy formation in football teams, Ribeiro et al. (2019) introduced a novel method for assessing meso-level synchronisation tendencies within and between subgroups of players – i.e., referred to as simplices, or relational structures (e.g., 2vs.1) that emerge during competition. To more accurately capture meso-level synchronisation tendencies during football performance, the present study aimed to develop and test a novel method of analysis, using a newly developed coordinate system, defined by the performance variables of angle and distance of players within relational structures (i.e., simplices) to each goal.

Accordingly, this study aims to: i) analyse synchronisation tendencies using new performance variables, specifically players' distance and angle relative to the goal; ii) compare synchronisation tendencies using traditional longitudinal and lateral displacement measures with those based on distance and angle to the goal, assessing potential differences in their informational value; and iii), verify whether synchronisation tendencies vary across different field zones, providing insights into how contextual constraints shape team coordination patterns.

4.2 Materials and methods

4.2.1 Materials

This work presents a case study, and the data was obtained through convenience sampling, meaning it was selected based on accessibility and availability. The positional raw data (2D) of 28 male professional football players from two teams (11 starting players and 3 substitutes per team), recorded during a professional league match, was provided by STATS. The validity and reliability of this tracking system has been quantified to verify the capture process and data accuracy (Bradley et al., 2009; Valter et al., 2006). These data were obtained, at a rate of 1Hz, on a playing field with effective playing area of 68m wide by 105m long, from a multiple-camera match analysis system recording the players' movements during performance, with the cameras located at the top of the stadium. The data provided by STATS was synchronized with additional annotation data referring to the ball possession (team A, none, team B). The annotation 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 (McHugh, 2012).

4.2.2 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.

4.2.3 Ecological variables: simplices and pitch location

The informational constrains resulting from the relative locations of teammates and opponents are characterized at a meso-level (between global metrics such as teams' convex hulls and dyadic relations between pairs of players) using sets named simplices. All the elements in a simplice, its players and goals, are linked by an hyperedge. Figure 4 illustrates the set of simplices identified in a particular match frame. Here, simplice σ_n is composed of players 8, 11, and 12 from the blue (A) team and 27 from the red (B) team, i.e., $\sigma_n = \{a_8, a_{11}, a_{12}, b_{27}\}$.

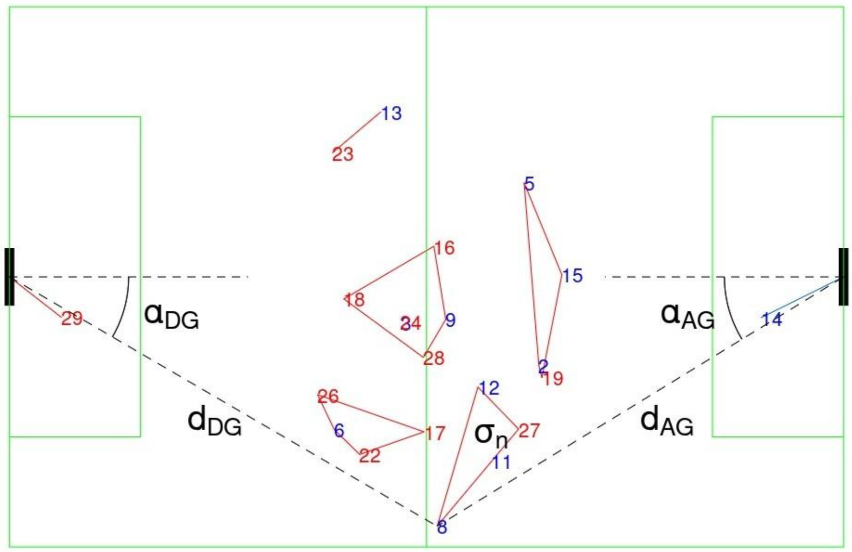

Figure 4. Schematic representation of simplices (player sets connected by hyperedges, e.g., $\sigma_n = \{a_8, a_{11}, a_{12}, b_{27}\}$) and analysis variables (distance and angle to attacked, d_{AG} and a_{AG}, defended goals, d_{DG} and a_{DG} represented for player a_8). The direction of the goal 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, as illustrated in Figure 5, 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.

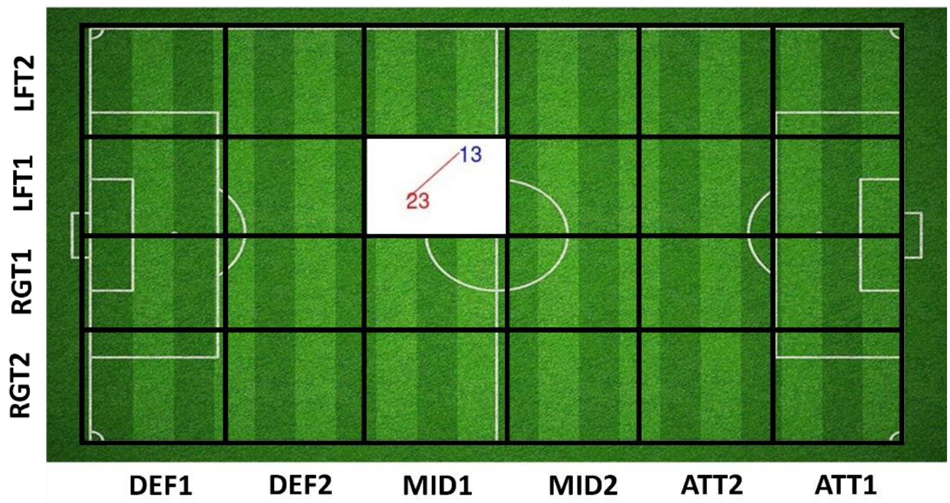

Figure 5. Field segmentation in 6 longitudinal (DEF – defensive third; MID – midfield third; ATT - attacking third) and 4 lateral zones (RGT – right side; LFT – left side). Location of simplices is defined by their centre of mass on the 6 by 4 cell grid, e.g., (MID1, LFT1) for the example simplice.

4.2.4. Variables under analysis and their synchronisation

In this paper the analysis variables are defined as the value of the distance and the angle to the attacked and defended goals ($d_{AG}, a_{AG}, d_{DG}, a_{DG}$) from the perspective of players in each simplice (as illustrated in Figure 4).

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. (2019) where the co-positioning of different *subgroups* (simplices) of players can be considered (Montbrió et al., 2004; Okuda & Kuramoto, 1991), 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 (2011), 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.For each of the four analysis variables ($d_{AG}, a_{AG}, d_{DG}, a_{DG}$) the within simplice synchronisation value is computed at each frame and associated to the possession status and field location as represented in Table 1. For comparison purposes, the synchronisation value for the longitudinal and lateral displacements, d_{Long} and d_{Lat}, is also computed.

Table 1. Sample of the synchronisation values computed from the positional data. (**Frame** – sample number, **Team** – team in possession, **ID** – simplice unique ID, **Location** – simplice qualitative location, **Synchronisation value** – simplice synchronisation value for the different analysis variables.)

Frame, k	Team	ID, n	Location		Synchronisation value, $\rho_{\sigma_{n,k},v}$					
			cx	cy	d_{AG}	a_{AG}	d_{DG}	a_{DG}	d_{Long}	d_{Lat}
783	A	3847	ATT2	LFT1	.845	.905	.736	.880	.769	.823
783	A	3446	DEF2	RGT1	.758	.645	.822	.888	.901	.899

4.2.5 Model and statistical methods

The effect of different variables on the synchronisation values are assessed using two different methods: pairwise difference between means and pairwise rank differences. 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 (Pitman, 1937), 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 (Brunner & Munzel, 2000; Karch, 2021). The statistic value, *W,* its degrees of freedom, *df*, 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.

For the study on how the synchronisation value varies between analysis variables and simplex locations the average of the synchronisation value is computed at each qualitative location over all frames, possession team, and simplice ID.

For assessing the statistical significance of the differences between the synchronisation averages across locations a generalized linear mixed effects model is used, as described by equation (1):

$$\varphi_{ji} = \ln\left(\frac{Y_{ji}}{1-Y_{ji}}\right) = \beta_0 + \sum_{j=1}^{N_i} \beta_i X_{ji} + u_{0i} + \varepsilon_{ji} \quad (1)$$

Here, we use the logit transformation, φ_{ji}, of the synchronisation value, i.e., the dependent (response) variable, $Y_{ji} \sim \text{Beta}(\alpha, \beta)$, and i is the frame index for simplice with ID j.

The two fixed independent factors (predictors) are the categorical variables indicating the longitudinal and lateral field zone, $cx \in \{DEF1, DEF2, MID1, MID2, ATT2, ATT1\}$ and $cy \in \{LFT2, LFT1, RGT1, RGT2\}$, the simplice ID, i, being used as random factor. The intercept, β_0, corresponds to pair $(cx, cy) = (MID2, LFT1)$ and X_{ji} is obtained from the indicator function on all other possible values for (cx, cy). To consider the interaction between factors cx and cy, indicator functions on their joint values are also considered. Random variables $u_{0i} \sim \mathcal{N}(0, \omega^2)$ and $\varepsilon_{ji} \sim \mathcal{N}(0, \sigma^2)$ correspond, respectively, to the by-subject, i.e., simplice ID, random intercepts and the sample-level model estimate error (residuals), for which normal distributions are assumed.

Procedures for computing both simplices' hyperedges and the analysis variables were performed using routines created by the authors coded in GNU Octave version 4.4.1and applied to each match frame sample. The regression model estimation and its statistical analysis were performed using R version 4.3.2 and the lme4 version 1.1.35 library.

4.3 Results

4.3.1 Synchronisation tendencies: Distance and angle to the goal

Overall, synchronisation tendencies varied according to field location and reference goals. When comparing synchronisation tendencies between angle and distance to goal, there is a tendency for distance to goal to elicit higher synchronisation tendencies. Additionally, the distance to goal elicited a more uniform distribution of synchronisation across the playing field, while the angle to goal revealed higher synchronisation tendencies in the side corridors.

When analysing the value of distance to the attacked goal (Figure 6a) and the defended goal (Figure 6d), synchronisation tendencies were found to be higher in areas closer to each goal, especially near the goal being attacked. Differences in synchronisation tendencies in different areas of the field *in between* the attacked and defended goals are minimal, as shown in Figure 6g.

Regarding the angle to the attacked goal (Figure 6b) and the defended goal (Figure 6e), higher synchronisation tendencies were observed in the side corridors, with a tendency for increased values near the reference goals in each analysis. Comparing synchronisation tendencies between the angle to the attacked goal and the defended goal (Figure 6h), greater differences were observed compared to the distance to goal.

Differences between player synchronisation tendencies, relative to distance to the attacked goal and to angle to the attacked goal (Figure 6c), are accentuated in the central corridor and areas near the defended goal. In turn, differences between synchronisation tendencies of distance to the defended goal and of angle to the defended goal (Figure 6f), are more pronounced in areas near the attacked goal.

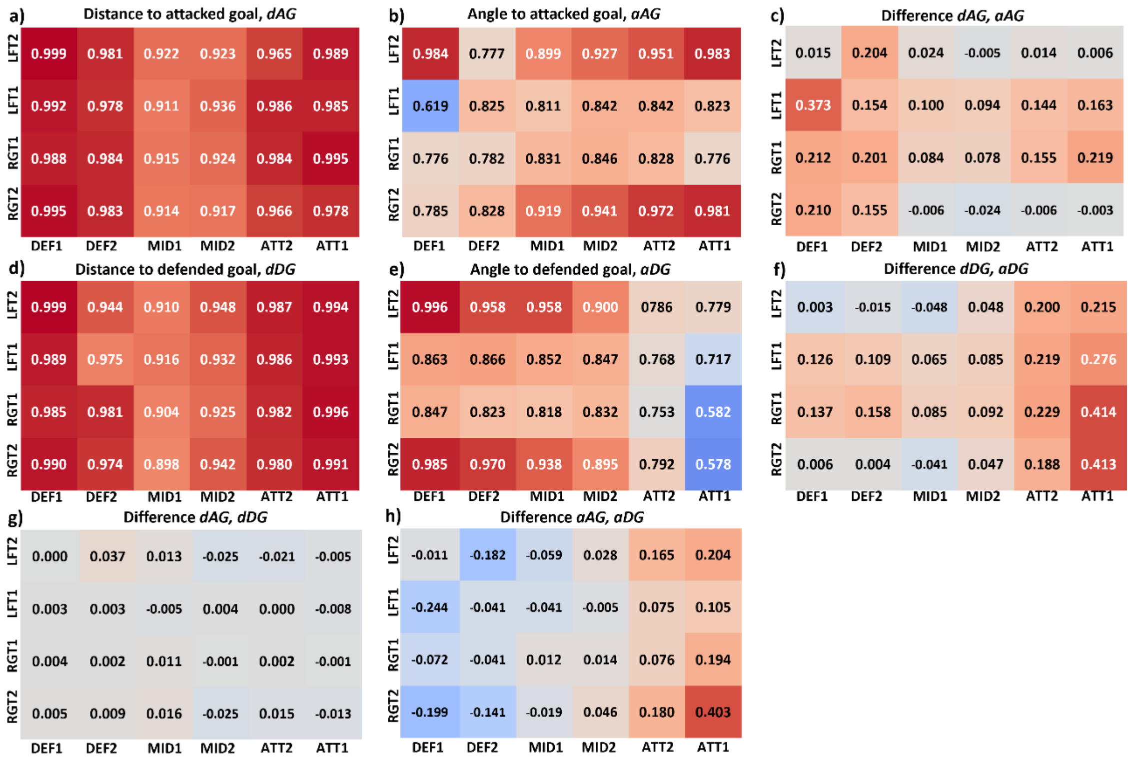

Figure 6. Illustration of heat-maps representing the simplice synchronisation tendencies regarding: a) distance to attacked goal; b) angle to attacked goal; c) differences between distance and angle to attacked goal; d) distance to defended goal; e) angle to defended goal; f) differences between distance and angle to defended goal; g) differences between distance to attacked goal and defended goal; h) differences between angle to attacked goal and 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.

4.3.2 Differences between the traditional coordinate system (lateral and longitudinal orientations) and the novel coordinate system (angle and distance to the goal)

4.3.2.1 Lateral Orientation vs Angle

Analysing synchronisation tendencies constrained by the lateral (y-axis) variable (Figure 7a), it is evident that the highest values were observed in the side corridors of the field, approximating results from analysis of the angle to goal (Figures 7b and 7d). However, a more detailed comparison between these two variables reveals considerable differences, whether in the side corridors or other areas (like the central corridor). The fact that the angle to goal separately considers both attacked and defended goals as reference points in the analysis may be a key factor contributing to the observed differences in synchronisation values (detailed results are provided in Tables 4 and 5 of the supplementary materials).

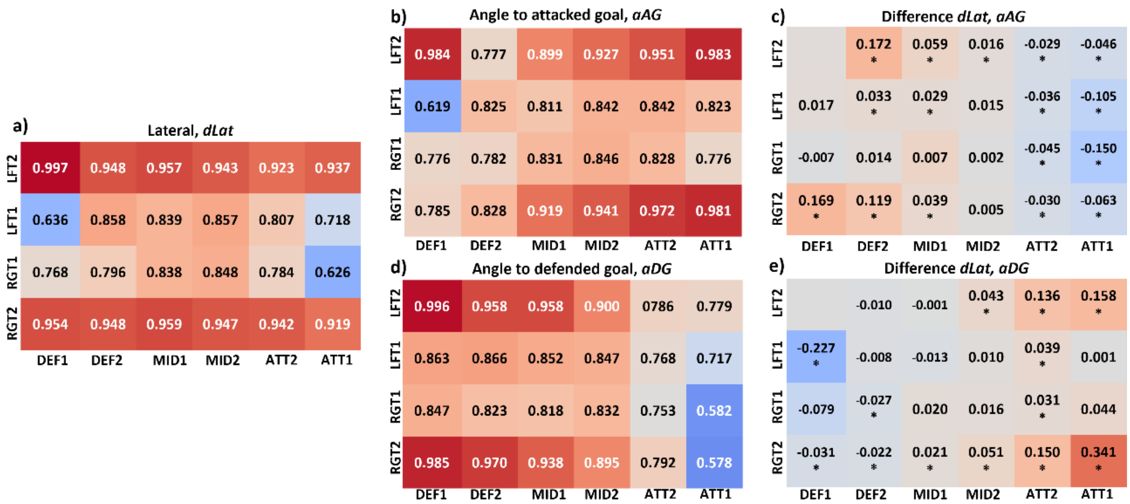

Figure 7. Illustration of heat-maps representing synchronisation tendencies regarding: a) lateral orientation on field (y-axis); b) angle to attacked goal; c) differences between lateral (y-axis) orientation and angle to attacked goal; d) angle to defended goal; e) differences between lateral (y-axis) orientation and 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.

4.3.2.2 Longitudinal Orientation vs Distance

Regarding the synchronisation tendencies between the longitudinal (x-axis) orientation variable (Figure 8a) and the distance to goal (Figure 8b and 8d), similar values were observed, resulting in minimal differences across various areas of the field, as shown in Figures 8c and 8e (detailed results are provided in Tables 6 and 7 of the supplementary materials).

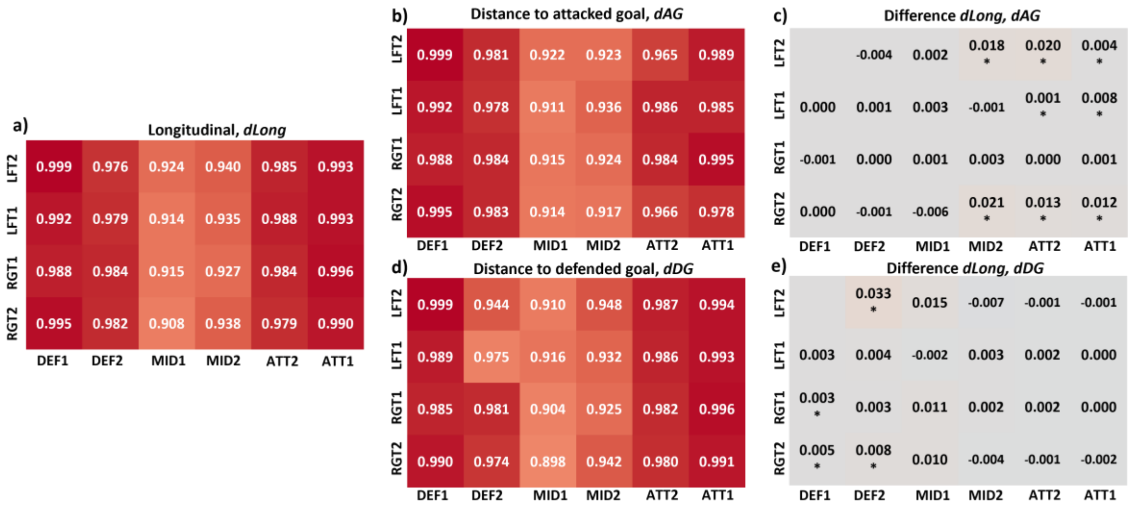

Figure 8. Illustration of heat-maps representing the synchronisation tendencies regarding: a) longitudinal (x-axis) orientation; b) distance to attacked goal; c) differences between longitudinal (x-axis) orientation and distance to attacked goal; d) distance to defended goal; e) differences between longitudinal (x-axis) orientation and 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.

4.3.3 Differences within field zones

Figures 9a and 9b indicate significant differences in average synchronisation tendencies within each specific area of the field, constrained by the different variables. Among the 24 zones into which the field was divided, the angle to the defended goal (Figure 9a: blue balls + two colour balls) shows the greatest variation, with significant differences in 9 zones. The values of distance, relative to the attacked and defended goals separately, present fewer differences between synchronisation averages, with the greatest impact on distance to attacked goal (Figure 9b: white balls + two colour balls), with significant differences in 7 zones.

These findings highlight the importance of understanding the events emerging in each area of the field, particularly in identifying the most prevalent simplice structures, and how they influence the synchronisation tendencies obtained.

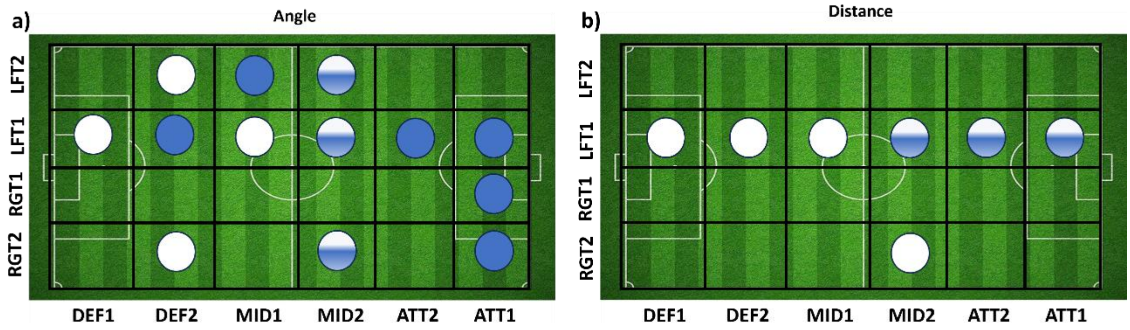

Figure 9. Illustration of a football field divided into 24 zones, represented by coloured balls indicating areas with statistically significant differences in synchronisation averages, considering: a) angle; b) distance. White balls represent zones with differences only at the attacked goal. Blue balls represent zones with differences only at the defended goal. Two-colour balls represent the zones with differences at both the attacked and defended goals.

To facilitate understanding, a detailed analysis of differences in synchronisation tendencies across different areas of the field was conducted. Table 2 presents the model estimated parameters for the angle to the attacked and defended goals (a_{AG} and a_{DG}), while Table 3 refers to the distance to the attacked and defended goals (d_{AG} and d_{DG}) analysis variables.

Table 2. Model parameters considering the angle to the attacked and defended goal, a_{AG} and a_{DG}

Field Zone, X_{ji}	Estimate, β_i		Std. Error		z value		Pr(>|z|)	
	a_{AG}	a_{DG}	a_{AG}	a_{DG}aDG	a_{AG}	a_{DG}	a_{AG}	a_{DG}
(Intercept)	**1.428**	**1.370**	0.039	0.039	36.780	35.140	**<.001**	**<.001**
cxATT2	0.088	**-0.310**	0.054	0.053	1.630	-5.880	0.103	**<.001**
cxATT1	0.038	**-0.480**	0.084	0.081	0.460	-5.940	0.648	**<.001**
cxMID1	**-0.169**	0.061	0.048	0.049	-3.500	1.240	**<.001**	0.214
cxDEF2	-0.109	**0.248**	0.067	0.069	-1.610	3.610	0.106	**<.001**
cxDEF1	**-0.610**	*0.376*	0.162	0.174	-3.770	2.160	**<.001**	*0.031*
cyLFT2	**0.520**	**0.450**	0.055	0.054	9.450	8.270	<.001	<.001
cyRGT1	0.057	-0.022	0.046	0.046	1.250	-0.480	0.210	0.633
cyRGT2	**0.790**	**0.525**	0.058	0.058	13.510	9.090	**<.001**	**<.001**
cxATT2:cyLFT2	0.153	*-0.264*	0.088	0.085	1.740	-3.110	0.082	*0.002*
cxMID2:cyLFT2	*0.319*	-0.234	0.150	0.141	2.130	-1.660	*0.034*	0.097
cxMID1:cyLFT2	0.017	**0.308**	0.079	0.080	0.210	3.850	0.834	**<.001**
cxDEF2:cyLFT2	**-0.582**	0.205	0.130	0.135	-4.490	1.520	**<.001**	0.128
cxDEF1:cyLFT2	0.908	-1.184	1.088	1.083	0.830	-1.090	0.404	0.274
cxATT2:cyRGT1	-0.038	0.037	0.076	0.075	-0.500	0.490	0.620	0.624
cxATT1:cyRGT1	-0.105	**-0.413**	0.116	0.113	-0.910	-3.660	0.365	**<.001**
cxMID1:cyRGT1	0.027	-0.124	0.069	0.069	0.390	-1.790	0.697	0.073
cxDEF2:cyRGT1	*-0.233*	-0.113	0.094	0.096	-2.490	-1.180	*0.013*	0.238
cxDEF1:cyRGT1	0.216	-0.275	0.213	0.226	1.010	-1.220	0.310	0.223
cxATT2:cyRGT2	0.119	-0.127	0.098	0.094	1.210	-1.350	0.225	0.178
cxATT1:cyRGT2	0.275	**-1.144**	0.228	0.209	1.200	-5.460	0.229	**<.001**

cxMID1:cyRGT2	-0.206	-0.009	0.088	0.088	-2.340	-0.100	0.019	0.922
cxDEF2:cyRGT2	**-0.725**	0.202	0.118	0.121	-6.140	1.680	**<.001**	0.094
cxDEF1:cyRGT2	*-0.527*	0.239	0.223	0.242	-2.370	0.990	*0.018*	0.323

Note: "Field zone" column indicates different field zones.

E.g. (Intercept) corresponds to $(cx, cy) = (MID2, LFT1)$; "cxDEF2" corresponds to $(cx, cy) = (DEF2, LFT1)$; "cxDEF2:cyRGT2" corresponds to the interaction between cx and cy at $(cx, cy) = (DEF2, RGT2)$. Significance level: **<.001**, *.001<<.050*

Table 3. Model parameters considering distance to the attacked and defended goal, d_{AG} and d_{DG}

Field Zone, X_{ji}	Estimate, β_i		Std. Error		z value		Pr(>|z|)	
	d_{AG}	d_{DG}	d_{AG}	d_{DG}aDG	d_{AG}	d_{DG}	d_{AG}	d_{DG}
(Intercept)	**2.404**	2.440	0.039	0.038	61.870	64.120	**<.001**	**<.001**
cxATT2	**0.392**	0.451	0.054	0.053	7.260	8.450	**<.001**	**<.001**
cxATT1	**0.564**	0.679	0.084	0.084	6.690	8.080	**<.001**	**<.001**
cxMID1	**-0.159**	*-0.117*	0.047	0.047	-3.380	-2.480	**<.001**	*0.013*
cxDEF2	**0.266**	*0.194*	0.069	0.068	3.860	2.840	**<.001**	*0.004*
cxDEF1	**0.606**	*0.580*	0.183	0.180	3.310	3.230	**<.001**	*0.001*
cyLFT2	*-0.136*	0.020	0.053	0.052	-2.580	0.380	*0.010*	0.705
cyRGT1	-0.036	-0.043	0.045	0.044	-0.810	-0.980	0.417	0.329
cyRGT2	**-0.200**	-0.014	0.055	0.055	-3.630	-0.250	**<.001**	0.800
cxATT2:cyLFT2	-0.160	-0.025	0.086	0.086	-1.850	-0.300	0.064	0.767
cxATT1:cyLFT2	-0.074	-0.181	0.149	0.147	-0.500	-1.230	0.620	0.218
cxMID1:cyLFT2	*0.195*	*-0.153*	0.076	0.075	2.550	-2.030	*0.011*	*0.043*
cxDEF2:cyLFT2	0.142	*-0.318*	0.132	0.129	1.070	-2.480	0.283	*0.013*
cxDEF1:cyLFT2	0.089	0.107	1.068	1.064	0.080	0.100	0.933	0.920
cxATT2:cyRGT1	-0.002	-0.075	0.076	0.075	-0.030	-1.000	0.978	0.319
cxATT1:cyRGT1	0.153	0.086	0.120	0.118	1.280	0.730	0.202	0.468
cxMID1:cyRGT1	0.099	0.030	0.067	0.067	1.470	0.450	0.142	0.651
cxDEF2:cyRGT1	0.112	0.144	0.096	0.095	1.160	1.520	0.245	0.130
cxDEF1:cyRGT1	0.139	-0.027	0.234	0.230	0.590	-0.120	0.552	0.906
cxATT2:cyRGT2	-0.113	*-0.240*	0.095	0.095	-1.200	-2.540	0.232	*0.011*
cxATT1:cyRGT2	-0.211	-0.149	0.225	0.227	-0.940	-0.660	0.350	0.512
cxMID1:cyRGT2	*0.272*	-0.036	0.084	0.084	3.230	-0.430	*0.001*	0.667
cxDEF2:cyRGT2	*0.300*	0.014	0.119	0.118	2.520	0.120	*0.012*	0.903
cxDEF1:cyRGT2	0.201	-0.320	0.246	0.242	0.820	-1.320	0.414	0.185

Note: "Field zone" column indicates different field zones.

E.g. (Intercept) corresponds to $(cx, cy) = (MID2, LFT1)$; "cxDEF2" corresponds to $(cx, cy) = (DEF2, LFT1)$; "cxDEF2:cyRGT2" corresponds to the interaction between cx and cy at $(cx, cy) = (DEF2, RGT2)$ Significance level: **<.001**, *.001<<.050*

4.4 Discussion

This study aimed to explore a novel method for analysing meso-level player synchronisation tendencies, using a newly developed coordinate system, defined by the performance variables of angle and distance of simplices relative to each goal. Importantly, the study did not seek to assess specific synchronisation tendencies as inherently more or less effective in achieving performance outcomes. Instead, the focus was to explore how such patterns reflect the adaptive behaviours of teams in response to competitive constraints, that is, how the synchronisation of movements between players

– teammates or opponents – varies based on their positioning on the field concerning the distance and angle to the goal.

Results obtained from this approach demonstrate an enhanced sensitivity of the proposed system in detecting synchronisation tendencies, particularly when compared to the traditional coordination system. Indeed, while synchronisation tendencies appear similar when comparing longitudinal and distance variables, more pronounced differences emerge when constrained by lateral and angle to the goal. Importantly, this novel approach is not intended to replace the traditional longitudinal-lateral cartesian coordinate system but rather to complement it, as each offers unique insights into player coordination dynamics. Together, their combined use can provide a more comprehensive understanding of how players synchronise movements during performance.

First, the synchronisation results, assessed through the distance to the goal, show that synchronisation tendencies are higher in areas closer to each goal, and particularly near the attacked goal. These findings contrast those reported by Carrilho et al. (2020) and López-Felip et al. (2018), who observed that when the ball was located in central areas of the field near the attacked goal, the mean synchronisation values decreased. Typically, near the attacked goal, the attacking player's space-time interactions are limited due to the proximity of defenders, who prioritize control of critical spaces to neutralize passing or shooting opportunities that could lead to a conceded goal. Conversely, to overcome these spatial-temporal constraints, attackers need to attract defenders, alternate between horizontal and vertical passes, increase the pace of ball circulation, and perform crosses from wide areas to generate goal-scoring opportunities. Depending on a team's strategy, a key performance objective may involve employing a low block (i.e., reducing space-time interactions to block the opponents' progression) or to transition into attack in the opposite direction of play, which will influence player synchronisation values accordingly.

Second, when analysing the angle to the goal, higher synchronisation tendencies were observed in the side corridors of the field, especially near the reference goals. These findings suggest that players prioritise controlling space relative to opponents in these areas by coordinating their movements with teammates (co-adapting), as captured by the angle-to-goal variable. Such insights shed light on the emergence of group synergies (Araújo & Davids, 2016), demonstrating how players synchronise their behaviors during game situations, primarily through coordinated diagonal movement patterns directed toward the attacking or defending goals (e.g., in 1v1 situations when the ball carrier attempts to dribble past a defender from the outside toward the inside corridor in order to create a passing or shooting opportunity).

Variations in synchronisation values suggest continuous adaptations influenced by the adapter component and driven by local interactions between players, within and between teams. These self-organizing tendencies, observed at the level of simplices, highlight the emergence of functional synergies, in which players co-adapt their behaviours based on locally created information (affordances), enabling them to regulate their positioning and movements in response to both teammates and opponents (Ribeiro et al., 2019). These synchronisation tendencies, therefore, should not be interpreted as end goals but rather as an emergent property that reflects the team's ability to self-regulate under varying performance constraints. For example, synchronised movements in the distance to the goal, particularly near the goals, indicate the capacity to maintain structural stability. Conversely, variation patterns in the angle variable, observed between the central and side corridors, may suggest exploratory behaviours as teams search for varied tactical solutions to overcome opposition. This dynamic interplay between synchronisation and exploration reflects the adaptive nature of synergies, in which players try to maintain a balance between structural organisation and performing innovative solutions - an equilibrium essential for effective team performance (Araújo & Davids, 2016). However, further analysis is needed to draw more robust conclusions.

The model of collective homeostasis (Santos et al., 2023, 2025) highlights this perspective by framing team coordination as a self-regulatory process to preserve functionality against continuous imbalances. Within this framework, variability is inevitable and essential, fostering resilience and adaptability to changing performance demands (e.g., Davids et al. (2013)).

4.5 Final Considerations

This study introduced a novel methodological approach to identify meso-level synchronisation processes in competitive football, focusing on the continuous adaptive demands of homeostatic regulation. The key findings highlight that the angle and distance to the goal comprise relevant variables influencing synchronised player behaviours during competitive performance. The method provides valuable insights into team self-organization by revealing synchronisation tendencies and the specific locations where each relational structure emerges. These findings are relevant for performance analysis, as they uncover key interaction patterns and spatial dynamics that can support tactical decisions-making and the design of more effective training sessions. Additionally, given that proximity to the goal has been shown to influence players' decision-making processes (e.g., Headrick et al. (2012), these insights may also help identify opponent tendencies or reveal structural weaknesses within a team.

As this is a case study, these variations highlight the challenge of generalizing findings across contexts, as what proves effective for one team or scenario may not apply universally. The study's limitations include a small sample size, the absence of ball data, and the lack of a direct relationship between the proposed synchronisation method and performance indicators, such as the number of ball recoveries or the creation of goal-scoring opportunities.

Despite these limitations, the method grounded in the collective homeostasis model provides promising avenues for future research. These include detailed examinations of synchronisation tendencies related to simplice structures in different field zones, considering the zonal differences observed across the analysed variables. In this context, exploring alternative spatial divisions beyond the 24 zones used in this study could be valuable to analyse the types of relational structures emerging during competitive performance. Recognising that different types of simplices can emerge throughout competitive performance (e.g., Ribeiro et al. (2020)), it would be valuable to explore how such structures influence synchronisation tendencies. Moreover, since synchronisation tendencies are known to vary across teams and contexts – being influenced by factors such as playing style, team system, player characteristics, and competition level (Folgado et al., 2014; Travassos et al., 2012) – future studies should investigate how these contextual variables shape the emergence and stability of synchronised behaviours. Furthermore, it would be relevant to explore whether synchronisation tendencies are associated with more frequent ball recoveries in specific field zones, depending on particular team structures, or whether synchronous or asynchronous tendencies increase the probability of scoring by disrupting defensive organisation.

Chapter 5

Capturing homeostatic behaviour in elite football teams: Synchronisation tendencies of cooperative and oppositional dynamics[4]

RICARDO SANTOS, JÚLIO GARGANTA, RUI J. LOPES, KEITH DAVIDS, & JOÃO RIBEIRO

Abstract

This study, investigating the collective homeostasis model, explores the importance of understanding both individual and collective behaviours in analysis of team performance in sport. Rooted in ecological dynamics, this model views collective behaviours 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 behaviours 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 behaviours) in football teams by analysing synchronisation tendencies of simplice structures, regulated by information on players' angle 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 team, mirroring the synergistic processes that underpin effective teamwork.

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

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[4] Santos, R., Garganta, J., Lopes, R., Davids, K., & Ribeiro, J. (2025). Capturing homeostatic behaviour in elite football teams: Synchronisation tendencies of cooperative and oppositional dynamics (Under Review in *Apunts Educación Física y Deportes*).

5.1 Introduction

Understanding individual and collective behaviours that underpin team coordination in sports is crucial for success (Passos et al., 2016; Silva et al., 2016; Vilar et al., 2013). The collective homeostasis model, recently developed by Santos and colleagues (2023), offers a novel theoretical perspective on how sports teams regulate their behaviours dynamically in response to performance demands. Grounded in ecological dynamics, this model suggests that collective behaviour emerges from homeostatic regulation, where players (as system components) continuously adapt (adapter component ability) to maintain structural integrity within survival parameters (Santos et al., 2023). 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 (Santos et al., 2023).

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* (Santos et al., 2025). Micro homeostasis consists of individualized effects allowing each player to co-adapt their behaviours during team performance (Santos et al., 2025). Macro homeostasis, on the other hand, refers to maintaining balance and stability in collective performance at the team level (Santos et al., 2025). 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; (Gibson, 1979a) (Santos et al., 2023, 2025). Additionally, distance and angle to the goal have been identified as critical spatiotemporal constraints impacting the emergence of team behaviours (López-Felip et al., 2018; Santos et al., 2025, under review; Vilar et al., 2014).

As an adaptive competitive entity, a football team depends on micro homeostasis, subtended to the principle of collective homeostasis (Santos et al., 2025). 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 (Araújo & Davids, 2011; Edelman & Gally, 2001; Seifert et al., 2016).

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., Duarte et al., 2013; Ribeiro et al., 2019). In this regard, the study of Duarte et al. (2013) 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. (2019) stated 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., 2017; Laakso et al., 2019) 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 (Carrilho et al., 2020).

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.

Given the aforementioned, 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 (Ramos et al., 2017; Ribeiro et al., 2020) 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.

5.2 Materials and methods

5.2.1 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 (Bradley et al., 2009; Valter et al., 2006). 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 (McHugh, 2012).

5.2.2 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.

5.2.3 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 10 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.

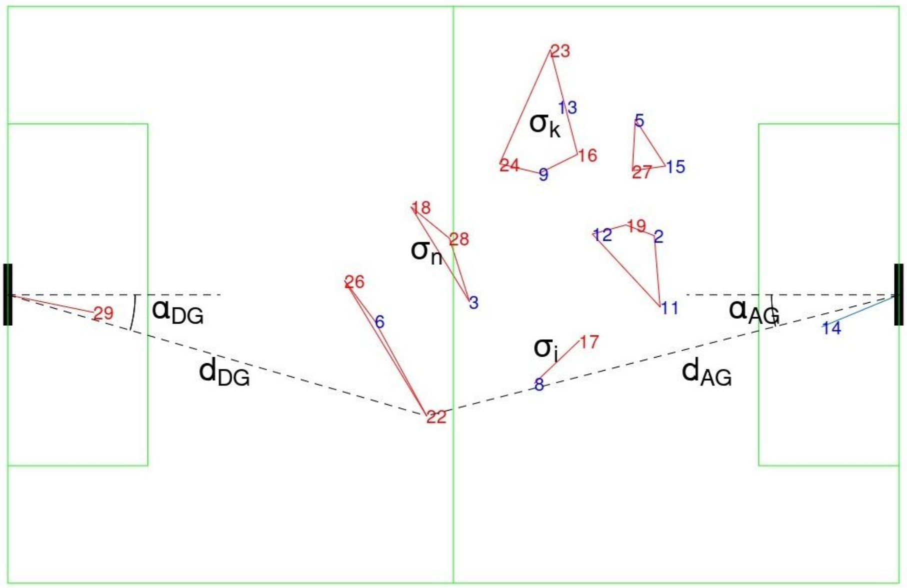

Figure 10 – Schematic representation of player structures (simplices, player sets connected by hyperedges, e.g., $\sigma_n = \{a_{18}, a_{28}, b_3\ 2vs.1\}$), $\sigma_i = \{a_{17}, b_8\ 1vs.1\}$) $\sigma_k = \{a_{16}, a_{23}, a_{24}, b_9, b_{13}\ 3vs.2\}$) and analysis variables (distance and angle to 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, using the process described in Chapter IV and the algorithm found in Appendix A (supplementary materials).

5.2.4. 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 10.

Using the same method as described in Chapter IV, the level of synchronisation for each of the analysis variables is computed using an extension to the process applied in Ribeiro et al. (2019) where different subgroups can be considered (Montbrió et al., 2004; Okuda & Kuramoto, 1991) and the phase for each player is computed based on methods of Varlet and Richardson (2011).

5.2.5 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 (Pitman, 1937), 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 (Brunner & Munzel, 2000; Karch, 2021). 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.

5.3 Results

5.3.1 Number and frequency of simplices

Results presented in Figure 11 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.

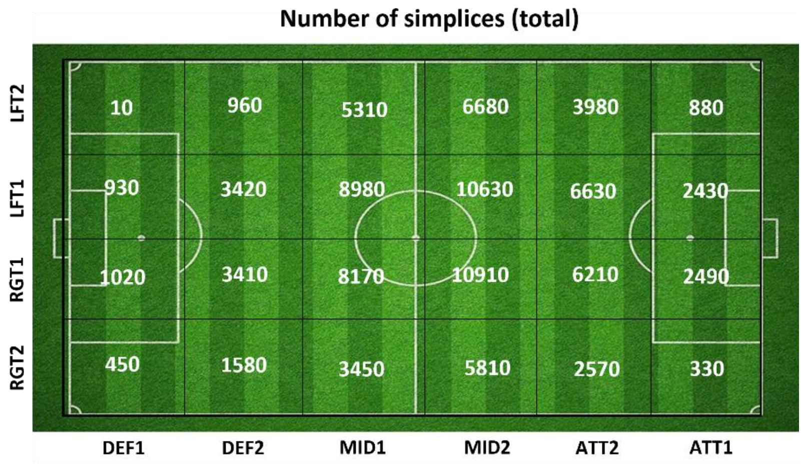

Figure 11. Representation of a football field with a total number of subsets (i.e., simplices) that occurred in each of the 24 zones. Field segmentation in 6 longitudinal (DEF – defensive third; MID – midfield third; ATT - attacking third) and 4 lateral zones (RGT – right side; LFT – left side)). The direction of the goal being attacked is from left to right.

Figures 12a, 12b and 12c 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 12d, 12e and 12f).

The 1vs.1 structure emerged more frequently, particularly in the side corridors of the pitch (Figure 12d), whilst the 1vs.2 structure appeared more often near the attacked goal (Figure 12e). Interestingly, in one area of the field (DEF1-LFT2, Figure12e), all observed simplices are 1vs.2 structures, possibly indicating some risk when facing numerical inferiority while in possession of the ball in a zone close to their defensive goal. The 2vs.1 structure showed higher values in the central corridor near the defended goals (Figure 12f), probably reflecting the defending teams' strategies to create numerical superiority (overload) in this critical area of the field to protect the goal.

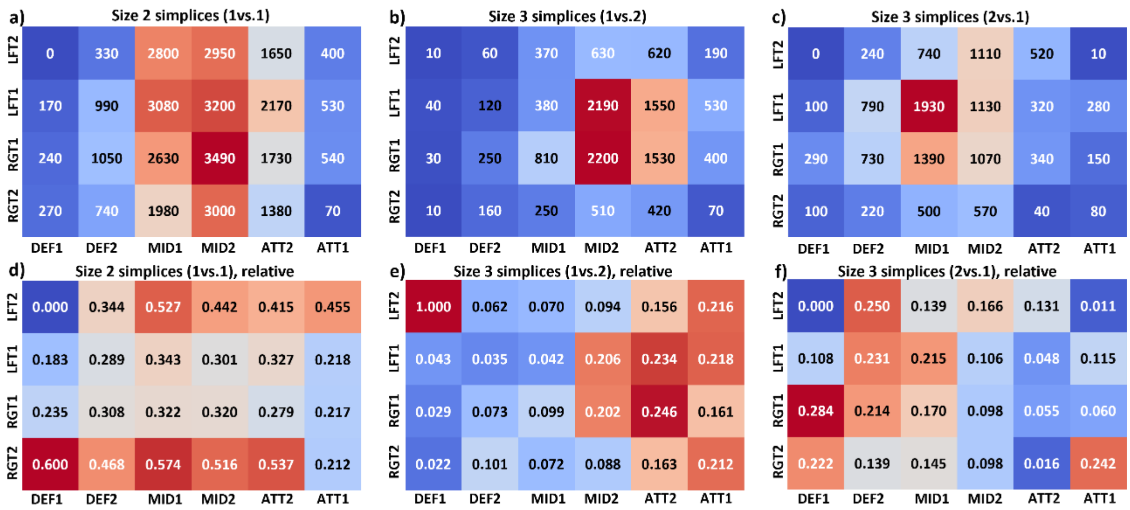

Figure 12. Heat-maps representing the number of occurrences regarding: a) simplices 1vs.1; b) simplices 1vs.2; c) simplices 2vs.1; and the density (%) regarding: d) simplices 1vs.1; e) simplices 1vs.2; f) simplices 2vs.1. Values of density range from 0 (a smaller number of simplices) to 1 (highest number of simplices). The direction of the goal being attacked is from left to right.

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

The remainder of this section analyses the 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).

5.3.2.1 Ball possession effect

When comparing synchronisation tendencies between the angle to the attacked goal (Figures 13a and 13b) and distance to the attacked goal (Figures 13d and 13e), 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 13c) compared to distance synchronisation (Figure 13f). 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 to the goal (9 zones) (detailed results are provided in Tables 8 and 9 of the supplementary materials).

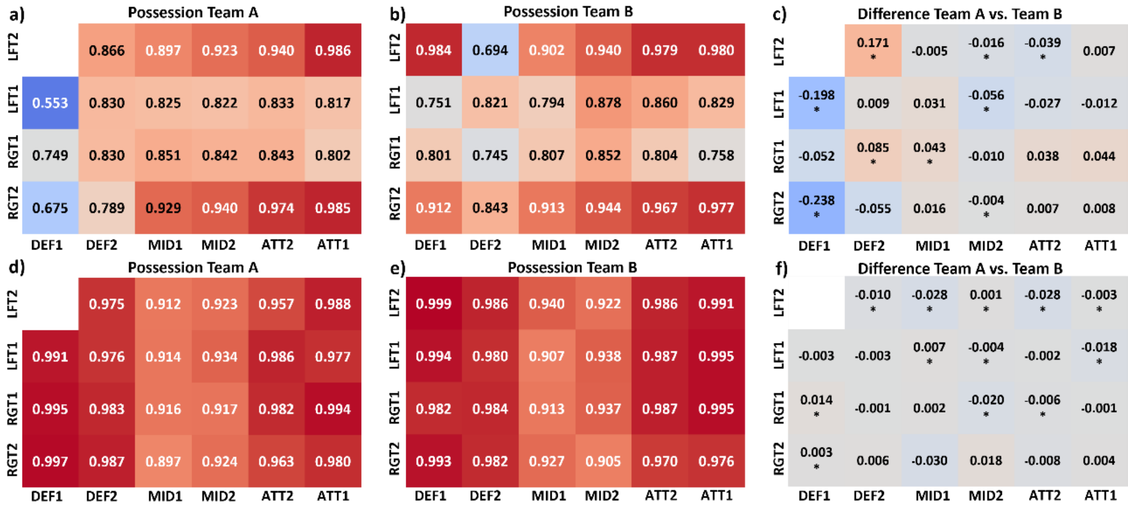

Figure 13. Illustration of heat-maps representing the simplices' synchronisation tendencies regarding: a) angle to attacked goal – team A with ball possession; b) angle to attacked goal – team B with ball possession; c) differences between angle to attacked goal considering ball possession; d) distance 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 14 and 15 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 14), 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.

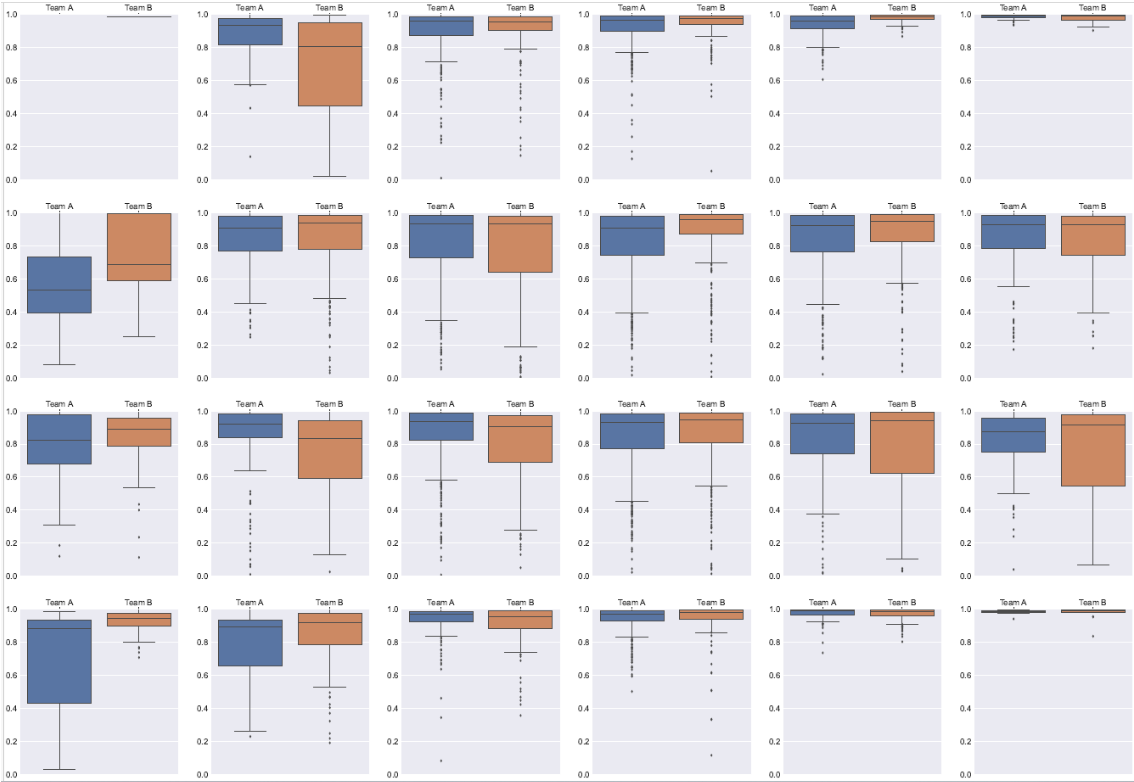

Figure 14. Illustration of box plots showing the distribution of synchronisation tendencies of team A and B during ball possession, relative to the angle to the attacked goal. The direction of the goal being attacked is from left to right.

Figure 15 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.

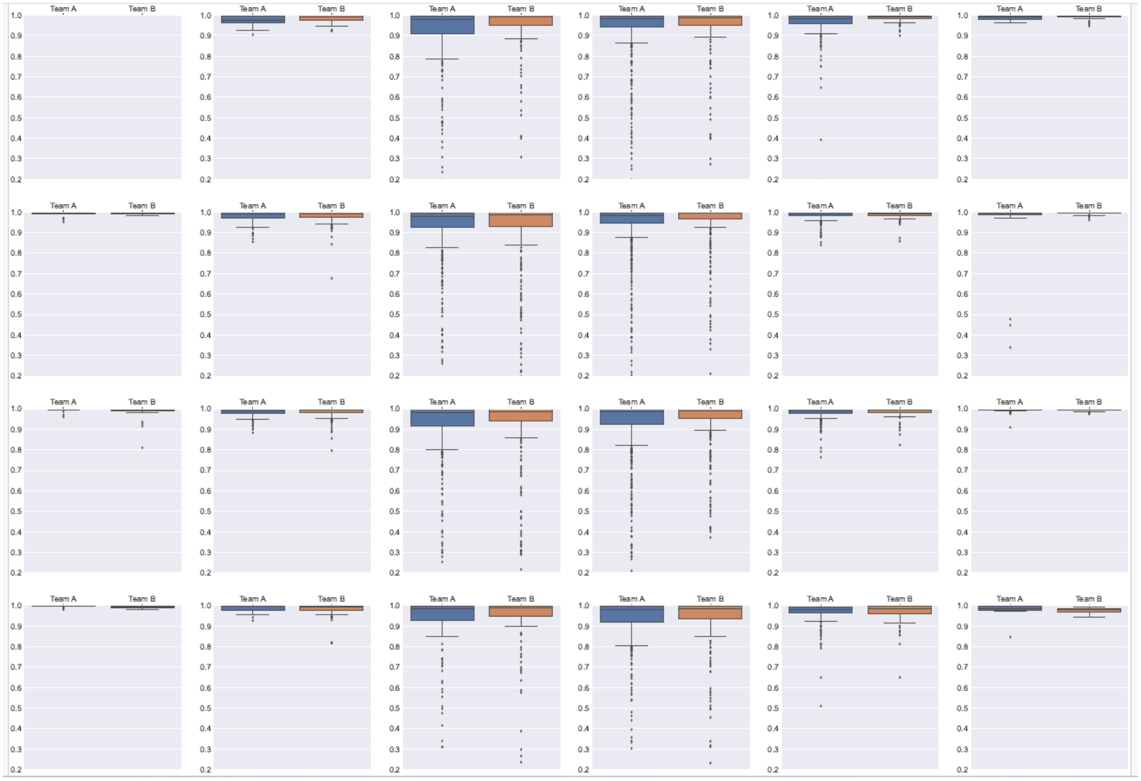

Figure 15. Illustration of box plots showing the distribution of synchronisation tendencies of team A and B during ball possession, relative to the distance to the attacked goal. The direction of the goal being attacked is from left to right.

The variables angle and distance to the defended goal were also analysed to assess the effect of ball possession on synchronisation tendencies. The data showed similar patterns to those observed for the variables angle and distance to the attacked goal (information available in the supplementary materials, Appendix B).

5.3.2.2 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 16a shows that simplices with size 2 present higher synchronisation tendencies in almost all areas of the field compared to simplices with size 3 (Figure 16b) and simplices with size 5 (Figure 16c). Figures 16d, 16e and 16f 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 significant differences compared to the smallest simplices of size 2 (detailed results are provided in Tables 10, 11 and 12 in the supplementary materials). Therefore, it is observed that, as the size of the simplices increases, the synchronisation tendency decreases.

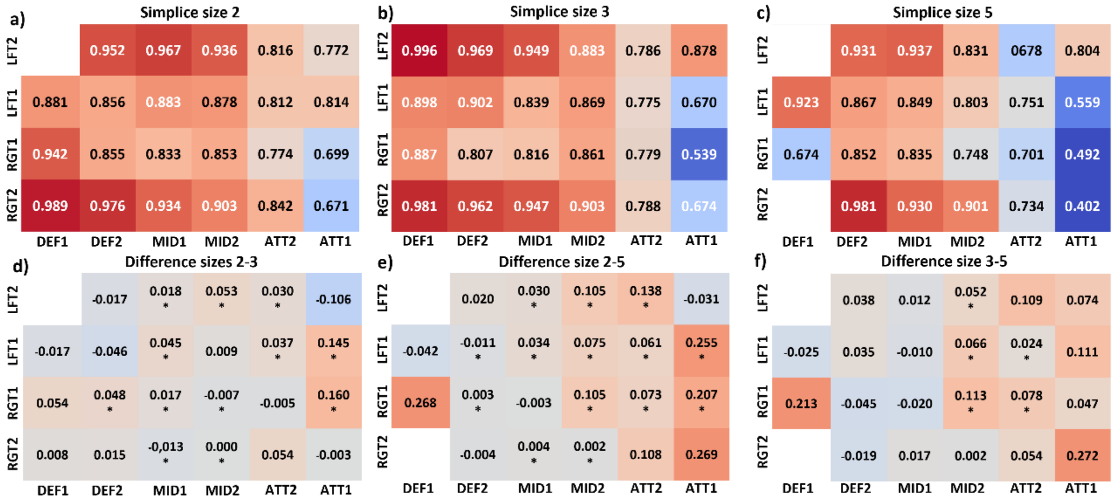

Figure 16. Illustration of heat-maps representing the simplices' synchronisation tendencies regarding: a) angle to defended goal – simplices size 2; b) angle to defended goal – simplices size 3; c) angle to defended goal – simplices size 5; d) differences between simplices size 2 and 3 considering angle 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 17a shows that simplices with size 2 exhibit higher synchronisation tendencies across almost areas of the field when compared to simplices with size 3 (Figure 17b) and simplices with size 5 (Figure 17c), consistent with the patterns previously observed for the angle to the goal. Figures 17d, 17e and 17f 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 13, 14 and 15 in the supplementary materials).

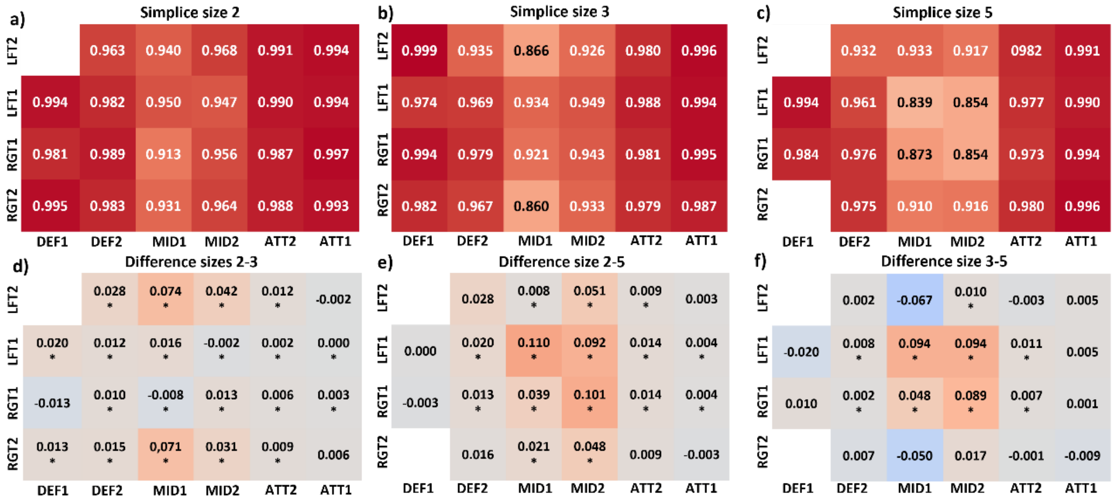

Figure 17. Illustration of heat-maps representing the simplices' synchronisation tendencies regarding: a) distance to defended goal – simplices size 2; b) distance to defended goal – simplices size 3; c) distance to defended goal – simplices size 5; d) differences between simplices size 2 and 3 considering 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 18 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.

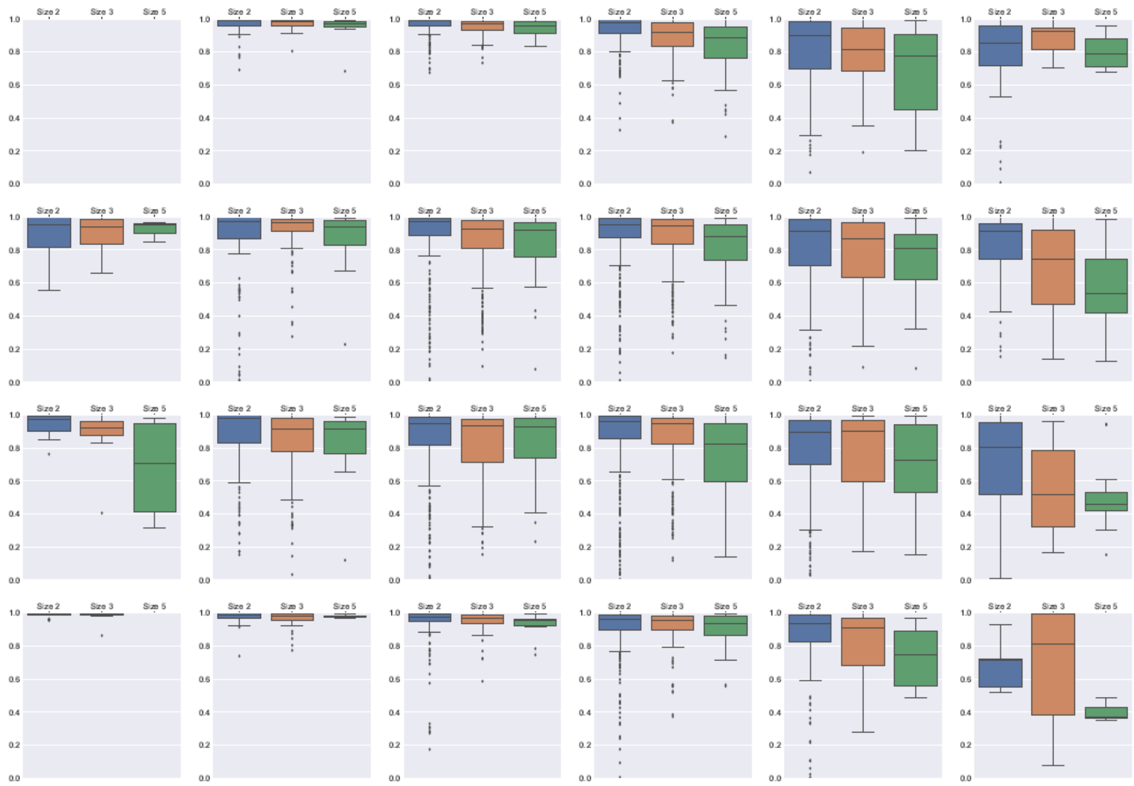

Figure 18. Illustration of box plots showing the distribution of synchronisation tendencies of the simplices sizes 2, 3 and 5 with reference to the angle to the defended goal. The direction of the goal being attacked is from left to right.

The analysis of the distance to the defended goal (Figure 19) 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.

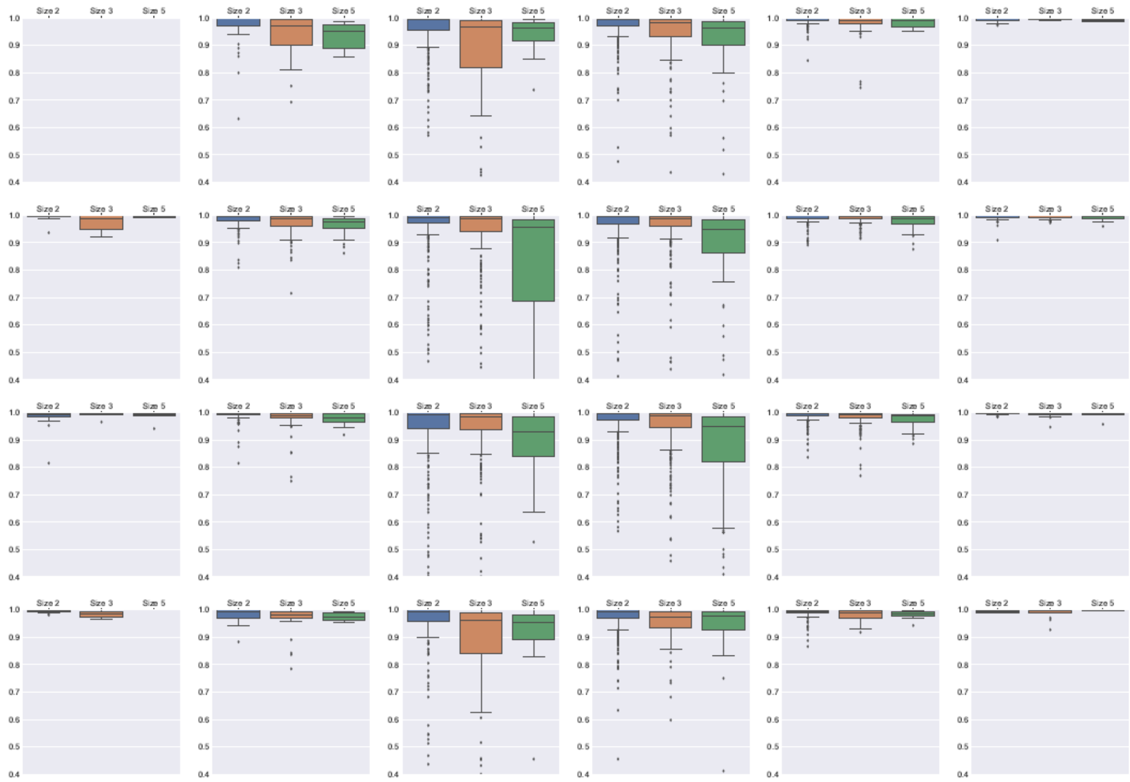

Figure 19. Illustration of box plots showing the distribution of synchronisation tendencies of the simplices sizes 2, 3 and 5 with reference to the distance to the defended goal. The direction of the goal being attacked is from left to right.

The variables angle and distance to the attacked goal were also analysed to assess the effect of simplice size on synchronisation tendencies. The data showed similar patterns to those observed for the variables angle and distance to the defended goal (information available in the supplementary materials, Appendix C).

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

When considering the effects of angle to the attacked goal (Figures 20a, 20b, and 20c), 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 20g, 20h, and 20i), synchronisation tendencies were also higher in the side corridors, however, the tendencies are reversed, with the highest values observed near the defensive goal.

Regarding distance to the attacked goal (Figures 20d, 20e, and 20f), 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 distance to the defended goal (Figures 20j, 20k, and 20l), 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 20a, 20c, 20d, 20f, 20g, 20i, 20j, and 20l 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.

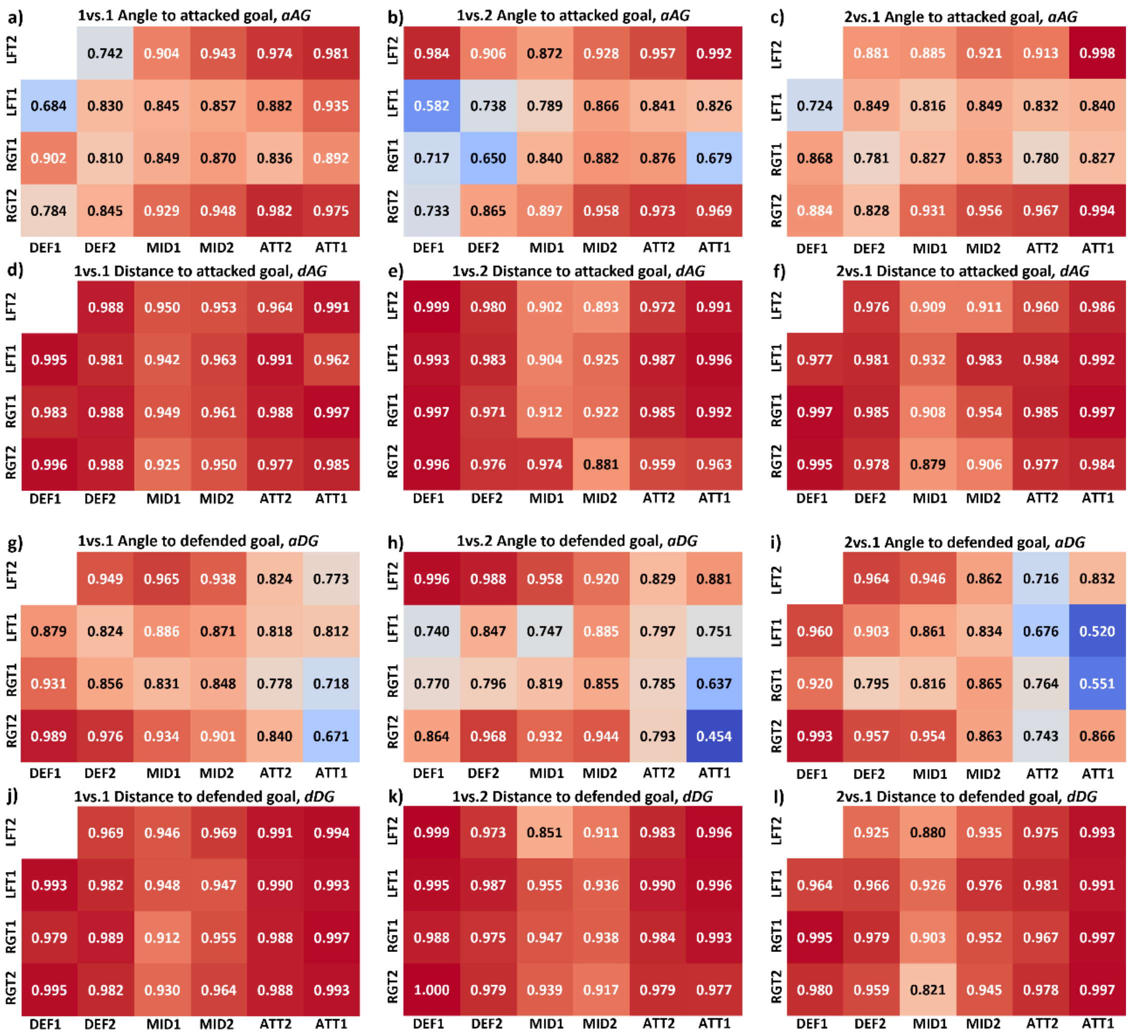

Figure 20. Illustration of heat-maps representing the simplices' synchronisation tendencies regarding: a) angle to attacked goal – 1vs.1; b) angle to attacked goal – 1vs.2; c) angle to attacked goal – 2vs.1; d) distance to attacked goal – 1vs.1; e) distance to attacked goal – 1vs.2; f) distance to attacked 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.

5.4 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 (Ribeiro et al., 2019). 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. (2017) and Ribeiro et al. (2020). 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. (2017), 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.

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. (2013), 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. Similar findings were reported by López-Felip et al. (2018) and Ribeiro et al. (2019), who noted variations in synchronisation tendencies depending on ball possession. However, it is important to note that our study differs from Ribeiro et al. (2019), 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 game. 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 of Duarte et al. (2013), 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 (Passos et al., 2016; Passos et al., 2009). 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. (2013) 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 (Riley et al., 2012; Silva et al., 2013). 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 (Seifert et al., 2024; Torrents & Balagué, 2006). 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 (Araújo & Davids, 2016; Passos et al., 2016; Santos & Passos, 2021). 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 (Davids et al., 2003).

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. 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.

A deeper understanding of how players behave and coordinate in these cooperative and oppositional dynamics – specifically regarding movement synchronisation at the meso-level provides crucial insights into the regulatory processes governing team performance. Specifically, it could be relevant to understand how the interaction 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.

5.5 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.

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.

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 (He et al., 2023). 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.

Chapter 6

General Discussion

To achieve the aims of this thesis, four studies were undertaken, with related articles prepared, framed by an ecological dynamics' framework. This chapter highlights the key findings from the experiments of this thesis, presents their theoretical and practical implications, outlines the main conclusions, and considers perspectives for future research.

6.1 Synthesis of main findings

Findings from this thesis provide a comprehensive overview of the role of collective homeostasis, demonstrating how teams maintain functionality and organisation during competitive performance. This work sought to contribute to both the advancement of theoretical knowledge in this field and the development of practical strategies to enhance understanding of the performance and cohesion of sports teams, particularly football teams, in highly competitive environments. The major findings of each study will be briefly discussed here to provide an integrated perspective of the overall thesis.

Chapter II presented theoretical insights on how sports teams, conceptualised as homeostatic regulatory systems, can continually self-organise their ongoing interactions to maintain team functioning and organisation during competitive performance. In the model, team performance is co-regulated as coordinated behaviours emerging through synergy (re)formation between performers (captured through simplice transformations) to adapt efficiently and effectively to satisfy emerging dynamical constraints of competitive environments. Understanding collective homeostasis in interpreting the self-organizing dynamics of sports teams facilitates identifying and analysing adaptive behavioural responses of teams, sub-groups, and individual players. As a starting point, a biological model of collective homeostasis comprises four critical components: a) players, b) set point, c) identifier, and d), adapter. Understanding the interrelated functions of model components is fundamental to designing practical training sessions and programs to develop self-regulating team performance. In performance analysis, identifying and disrupting key moments (i.e., disrupting a specific set point, such as not closing spaces between players after losing the ball near the defended goal), can help understand how teams handle critical situations during a competitive match.

Based on these insights and given the extraordinary capacity of humans to construct and adapt ecological niches, chapter III explores the creation of enriching sporting contexts for the development of adaptive player-environment interactions in competitive team sports. This adaptation model emphasises the importance of creating a sports niche rich in shared affordances (Silva et al., 2013), enabling team coordination through development of micro and collective homeostasis in different sub-phases of competitive performance (i.e., attack, defence and transitions). In a homeostatic sports system, principles of play advocated by coaches allow players to intentionally coordinate and adapt their actions to shape a team's collective identity. The team's identity is shaped by developing collective attractors (stable system states) emerging at specific complexity scales in competition, through constraints manipulation by the coaching and supporting staff. These ideas have key implications for implementing team sports training and performance preparation models to improve the homeostatic regulation process. Specifically, the focus is on enhancing the self-regulating tendencies of players by creating practices which encourage them to adapt their behaviours to dynamic performance contexts.

Chapter IV explores the emergence of synchronisation tendencies in elite football teams, focusing on how players coordinate their actions within specific sub-phases of play to achieve performance goals under various competitive constraints. The study examines the player-environment relationship, analysing how ecological variables – such as angle and distance relative to goal – influence collective decision-making. The chapter introduces a novel method employing a newly developed coordinate system to analyse meso-level synchronisation tendencies, to define angle and distance values of player subgroups (simplices) relative to the goal. This approach, designed to capture the continuous adaptive needs of homeostatic regulation in performance, successfully recorded synchronisation tendencies between players emerging at the meso-level scale. Results indicate that this system presents different sensitivity in detecting synchronisation tendencies between players than traditional coordination analysis methods. This sensitivity is specifically related to spatial zones, the type and structure of simplice, and ball possession. However, it is important to note that this analysis did not evaluate differences between teams with distinct playing styles or tactical systems. The key performance variables, angle and distance to goal, are critical constraints on players synchronized behaviours during the attacking and defending sub-phases of play.

Following this methodological proposal, chapter V explores the importance of understanding individual and collective behaviours in performance analysis of sports teams. As mentioned throughout this work, the collective homeostatic model views a sports team`s collective behaviours as a homeostatic process that maintains structural integrity 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 behavioural patterns observable at the macro-level (Ribeiro et al., 2019). These patterns and their synchronisation level reflect homeostatic regulation, directly impacting team stability. Therefore, this study focused on capturing micro homeostasis (reflected at the meso-level scale) in football teams by analysing synchronisation tendencies of simplice structures, regulated by information on the angle and distance of players to the goal. The results revealed that 1vs.1, 1vs.2, and 2vs.1 simplice structures appear to be most frequently observed, with both the type of structure and ball possession playing a significant role in synchronisation dynamics in a collective system. Additionally, the size of the simplice influenced synchronisation, with larger simplices exhibiting lower synchronisation values. Since the collective scale emerges from interactions at lower complexity levels (micro-meso interactions), understanding these dynamics is essential for grasping the collective homeostasis regulation within a team. These dynamics reflect the synergy processes that underpin effective teamwork.

Building on this understanding, this novel method for observing and reporting synchronisation tendencies, presented in chapters IV and V, can provide coaches with valuable information to effectively structure and monitor player transactions during performance and training sessions.

6.2 Theoretical implications

"*A truly stable system expects the unexpected, is prepared to be disrupted, waits to be transformed*"

Tom Robbins (1980)

In high-performance sports, the intensity of competition continues to grow. The pursuit of optimal training tools and methodologies aimed at enhancing the performance of athletes and teams, focuses on identifying well-adjusted and coherent models to better understand the sporting environment.

Human behaviour in competitive contexts is complex and cannot be analysed simplistically. From a systems perspective, sports teams have been conceptualised as complex adaptive systems composed of integral components (i.e., the players) (Davids et al., 2013; Davids & Araújo, 2025). System components interact within the performance environment in a dynamic, interdependent and functional manner, revealing emergent, self-organizing tendencies in behaviour to achieve task goals (Davids et al., 2015).

Understanding the nature of self-regulatory tendencies in complex adaptive systems – specifically those that sustain the co-adaptive performance interactions of competing teams – is essential for developing methodologies for performance analysis.

Performance analytics in each sport relies on a certain set of assumptions about the analysed performance. Therefore, the design of information systems for performance analysis should be grounded in an explicit performance model within a specific team sport.

Concerning the central theme of the collective homeostasis model, the goal is not to claim the discovery of new phenomena or propose a standalone theory. Very few research programmes in science can make that claim. Instead, this model reframes and applies well-established principles – such as self-regulation, self-organization, or synergies – while highlighting homeostatic adaptation as a key organizing principle in sports teams, particularly football teams. Since performance analysis is not an end, but rather a means, to derive implications for sport training and competition, it is essential to have a clear and explicit understanding of what constitutes a sport system, such as a competitive match. To contribute to this systemic vision of the game, we propose a model that deepens the understanding of self-regulatory tendencies in sports teams.

The collective homeostasis model consists of four components: i) **players**, self-regulating agents who achieve intended performance goals by coupling perception and action systems; ii) **set point**, a set of principles of play that guide or shape a sports team`s performance approach; iii) **identifier**, a set of aggregating ideas and intentions shared by players; and iv), **adapter**, a self-organising process promoting the search for adaptive responses aligned with intended goals. Ascribing different parts of a sports team to different roles in the homeostatic adaptive system framework, can lead to a better understanding of team behaviours, as detailed in Chapter III.

In modern team games, teams face increasing demands for an additional evolutionary leap. This perspective mirrors the broader dynamics of life itself, constantly adapting, resisting, and projecting into the future – an idea fundamental to creativity and survival. Teams with efficient homeostatic regulatory processes are better equipped to deliver adaptive responses in competitive contexts.

This programme thesis suggests that a well-adapted team approaches a game holistically, treating attack and defence not as separated phases but as interconnected states within a continuum of adaptive readiness. This perspective aligns with the concept of dynamic equilibrium in living systems, highlighting the ongoing tension and balance between stability and change.

Achieving a balance in feedback processes is essential for maintaining a team´s performance adaptability. Feedback processes promote corrective actions to ensure system cohesion and stability, especially during perturbations caused by opposing team's actions. By integrating adaptive regulation, teams can effectively navigate the dynamic nature of competitive gameplay, demonstrating resilience in preserving their identity, coherence, and adaptability in performance, responding to emergent challenges in context. This balance ensures that a collective system remains robust yet flexible, aligning with the principles of collective homeostasis in high-performance contexts.

This concept is closely linked to the skill of maintaining and forming new structures (or microstructures) of interaction, captured by the concept of simplices. These microstructures enable players and teams to respond effectively to performance contingencies within a given context, allowing them to navigate disruptions caused by opponent actions, strategic shifts, or internal imbalances.

To address these challenges, collective homeostasis emerges as a critical organizing principle for sports teams. Drawing inspiration from biological systems, it highlights a collective system's interconnected and adaptive nature, for example, allowing a sports team to function as cohesive units rather than mere collections of individual players. Through processes of self-organization and synergy formation, collective homeostasis enables teams to regulate their behaviours, achieving dynamic equilibrium even under variable conditions.

This regulatory process operates across multiple levels of complexity, from the individual player to the team's collective performance. Coordinated interactions among players foster adaptability and resilience, ensuring effective performance despite changes in strategy, opponent actions, or other game constraints.

To deepen understanding of these dynamics, experimental studies in Chapters IV and V examined the adaptive behaviours of teams under different competitive constraints. Specifically, we investigated how the synchronisation of movements between players (teammates and opponents) varies based on field positioning, ball possession, and size and type of simplice structure.

The findings revealed that 1vs.1, 1vs.2, and 2vs.1 simplice structures were most frequently observed, consistent with data reported by Ramos et al. (2017) and Ribeiro et al. (2020). These configurations emerged predominantly in specific field areas – 1vs.1 situations in the side corridors; 1vs.2 near the attacked goal; 2vs.1 in the central corridor near the defended goal. These results emphasize teams' adaptive behaviours in exploiting numerical advantages in strategic playing zones while also revealing potential defensive vulnerabilities, such as the lack of defensive coverage in 2vs.1 situations near the goal of the defending team's goal.

Contextual factors significantly influenced synchronisation dynamics. Higher synchronisation tendencies were observed in areas closer to the goals, particularly in the attacking zones and side corridors. These findings align with the notion that players and teams coordinate their movements more intensively in high-pressure zones either to protect and control critical spaces when defending or creating goal-scoring opportunities when attacking. However, this observation contrasts with findings of Carrilho et al. (2020) and López-Felip et al. (2018) who reported lower synchronisation near the attacked goal's central areas.

The analysis also highlighted the role of ball possession in shaping synchronisation patterns. The differences between the two teams suggest how tactical and strategic approaches influence the cooperative and oppositional dynamics between players.

Although not directly analysed, the self-organization processes underlying the formation and transformation of simplices were evident in the continuous (re)adjustments players made during play. These patterns reflect individual and collective homeostasis tendencies as teams dynamically adapt to maintain structural integrity under varying competitive constraints.

The adaptive process outlined here is not about achieving perfection but about demonstrating effectiveness and versatility in responding to the diverse constraints of competitive sports. For instance, a team might adapt its strategies mid-game in response to an opponent`s sudden tactical shift, showcasing emergent behaviour analogous to how biological systems regulate themselves in unpredictable environments. In this context, collective homeostasis emphasizes the critical roles of adaptability and resilience in sport performance. By focusing on being *good enough* rather than striving for perfection, teams are better equipped to navigate the inherent uncertainties of competition and enhance their chances of success.

This perspective challenges the traditional view of homeostasis as a property solely focused on maintaining system integrity. Instead, it reframes homeostasis as a pivotal factor in the development and evolution of complex systems, emphasizing its role in driving adaptive and dynamic behaviour over time (Torday, 2015b; Torday & Rehan, 2017).

In the realm of sport, the adaptive responses of teams provide a fascinating parallel to the biological concept of evolution. Evolution, in biology, refers to an organism's growth, improvement, or development over time. It involves both transformations within species and the emergence of new ones, driven by interactions with their environments (Losos et al., 2014).

The interaction between an organism and its environment is central to this process. As the environment changes, organisms adapt, becoming better suited to their surroundings. However, this ecological process is reciprocal and bidirectional (Ribeiro et al., 2019); the organism can also influence and modify its environments, shaping conditions that support their growth and survival (Gibson, 1979a). In sports, a similar dynamic unfolds (Rothwell et al., 2021). Teams constantly adapt to the competitive environment, responding to various challenges. For instance, players manipulate opponents' space and time to create advantageous conditions in offensive and defensive sub-phases of play. This adaptation process aligns closely with the concept of collective homeostasis, where achieving balance in these changes is essential for a team's success. Homeostatic regulation, like in biological systems, enables teams to dynamically respond to changes while maintaining a stable and effective performance state. Drawing on these parallels between biological evolution and team dynamics, this thesis provides insights into how adaptation and regulation function together to optimize performance in the ever-changing world of competitive sports.

Adaptation and efficiency can be enhanced in sports teams through niche construction (Rothwell et al., 2023). This concept refers to the deliberate modification of practice environments to create stable patterns of interaction, known as collective system attractors, that support team functionality and development. Coaches modify practice constraints to shape the sports niche, employing strategies such as altering game rules, prioritising specific space and locations, adjusting numerical relations in small-sided and conditioned games, introducing *jokers* into games, and using a wide range of equipment and technologies (Sarmento et al., 2018). These interventions adjust the specified information available to players, driving the emergence of collective attractors – stable behavioural tendencies aligned with the principles of a specific game model (Ribeiro et al., 2019). This pedagogical strategy enhances a team`s capacity for collective homeostatic regulation by developing the model's components.

Collective attractors play a pivotal role in maintaining collective homeostasis by functioning as a "preferred state" for team performance. These attractors refer to stable patterns or states in which a dynamic system (individual player or the team as a whole) tends to stabilize, even amid variability or disturbances (Kelso, 1995). In the context of sports teams, these attractors often manifest as consistent interaction patterns observed during gameplay (Gorman et al., 2017; Travassos et al., 2016). They provide a reference framework for balancing the system while enabling adaptation to both internal and external perturbations.

Collective homeostasis relates to the capacity of a team, understood as a biological system comprising multiple hierarchical levels of organisation (individual, group, sectorial, inter-sectorial, and collective), to maintain balance and stability. System equilibrium is achieved as the team adapts to external challenges, such as opposition strategies, and internal factors, such as intentions, fatigue, emotions, or stress (Cannon, 1932; Damásio, 2017; Davids et al., 2013). These adaptations ensure continued functionality and success. This adaptive capacity is essential for enabling teams to remain flexible and produce efficient, effective responses in competition to various perturbations, including challenges posed by opposing teams (Seifert et al., 2013). After making necessary adjustments, a team tends to stabilize into regular patterns aligned with its collective attractors. These attractors are intricately connected to the functional dynamics of the team and are shaped by the performance principles established by the coach.

By linking sports niche construction with the dynamics of collective attractors and homeostasis, it becomes clear that the deliberate structuring of training environments and gameplay strategies plays a fundamental role in fostering a team's ability to adapt while maintaining stability. This interaction highlights the synergy between adaptability, efficiency, and stability, emphasizing the importance of well-designed practice environments in optimizing team performance. Exposing players to challenging and diverse practice contexts promotes the development of adaptive responses, enabling teams to regulate behaviours essential for game success (Davids et al., 2013; Renshaw et al., 2019). This process benefits the team and shapes the game`s evolving characteristics.

Over time, the game's evolution has centered around solving tactical challenges (Teoldo et al., 2021). This process of solving tactical challenges aligns closely with the collective homeostasis model, where team behaviours – guided by attractors – contribute to the identity expressed through tactical behaviours (highlighted in Chapter II). These dynamics foster continuous growth and the emergence of diverse responses that shape the game`s evolutionary trajectory.

Each team develops unique playing styles, yet the most successful and aesthetically appealing styles share common attributes: technical excellence, diversity, intelligence, and creativity (Memmert, 2015; Torrents et al., 2020). These attributes, supported by collective homeostatic regulation, emphasize the crucial role of cooperation in developing players and teams, celebrating the balance between individuality and collective effort.

In summary, the interplay between collective homeostasis and sports niche construction plays pivotal roles in shaping sports teams' adaptability, identity, and success of sports teams. By fostering environments that challenge players and promote cooperation, teams not only enhance their chances of success but also contribute to the evolving dynamics of the game itself.

The thesis focuses on conceptualizing sports teams as collective homeostatic systems, particularly football teams. This is important because it has been noted that each type of sports performance environment has a specific 'form of life' (Wittgenstein, 1966; Woods et al., 2020), predicated on unique patterns of behaviour, knowledge and skills, as well as customs and cultural constraints (Rietveld & Kiverstein, 2014). Consequently, interpreting and analysing this model requires careful consideration and appropriate adjustments to account for the specific characteristics of different sports.

6.3 Practical applications

"Cooperation tends to go hand in hand with conflict... even the closest union is rife with subterfuge and conflict... Conflict is part of life, not only between the different sides of a war, but also between individuals whose interests lie, generally aligned."

Nichola Raihani (2024)

Throughout, this thesis has sought to establish that collective homeostasis is critical for understanding the dynamic interactions within sports teams and their impact on overall performance. This concept captures a team`s ability to maintain a type of dynamic equilibrium during performance, enabling coordinated and efficient responses to the evolving demands of the game.

Achieving this balance relies on regulatory processes that promote stability by counteracting disruptions and preserving the team´s structural integrity. While the experimental studies of this thesis did not explicitly analyse feedback processes, synchronisation tendencies and the ability to adapt to tactical situations – such as adjusting positioning or exploiting vulnerabilities – may reflect feedback principles. For instance, defensive adjustments in response to emerging threats help restore balance by reorganizing player positioning. Similarly, synchronisation is evident when players adapt their relative positions and movements to maintain structural coherence, particularly when goal proximity or player mismatches (e.g., 2vs.1) threaten team organisation.

This dynamic equilibrium is essential for the team´s capacity to operate harmoniously while adapting to tactical and contextual changes, and is related to the concept of 'metastability' in coordination dynamics (Kelso, 1995). Collective homeostasis plays a pivotal role in shaping performance outcomes by fostering both stability and flexibility, which is functional when a team reaches a metastable region of performance.

The effectiveness of this process is deeply intertwined with the quality of cooperation among players. Cooperation requires coordination and harmony, ensuring that individual player´s actions contribute to shared performance objectives. A key practical manifestation of collective homeostasis is synchronisation – the spontaneous coordination of oscillating systems, achieved when individual components adjust their rhythms to align with one another (Strogatz, 2003). In a sports team, synchronisation describes the ability of team members to align their movements, decisions, and actions with one another and respond to opponents, thereby sustaining a cohesive team structure (Folgado et al., 2018).

Within a team, this performance tendency demands constant adjustment and adaptation, as players must align their efforts not only in response to their opponents' dynamic strategies but also to their teammates' positional adjustments, considering factors such as the location on the field or proximity to the goals. During a game, the effectiveness of a team`s cooperation hinges on its ability to balance shared goals – where the perspective of shared affordances, as highlighted by Silva et al. (2013), plays a crucial role – with the inevitable conflicts that arise. This interplay between cooperation and conflict highlights the complexity of team dynamics, where alignment and discord coexist and influence performance.

Understanding these dynamics motivated the development of the new method presented in Chapters IV and V. This method is based on hypernetworks and utilizes a new coordinate system defined by the performance variables of angle and distance of simplices to the goals. It captures the synchronisation of movements within the relationships of cooperation and opposition established between players. This approach highlights meso-level synchronisation by analysing these variables, providing deeper insights into how teams manage decisive situations during gameplay.

Before delving into a more detailed analysis of the results from methodological and experimental studies and their applicability, it is important to highlight that the focus was not on assessing specific synchronisation tendencies as inherently "better" or "worse" for achieving performance outcomes. Instead, we aimed to explore how these patterns reflect the adaptive behaviours of teams responding to competitive constraints.

The data presented in Chapter IV demonstrate that synchronisation tendencies vary depending on the variables analysed and the location on the field. The distance to the goal reveals higher synchronisation tendencies in areas closer to the goals, particularly near the attacked goal. In contrast, the angle to the goal shows higher synchronisation values in the side corridors of the field, with particularly high values near the reference goals in each analysis.

The self-organization process is reflected in players' continuous (re)adjustments in response to changes induced by the confrontation between teams. These adjustments result in emerging patterns, such as variations in the synchronisation tendencies of the distance and angle to the goal, as evidenced in this study. Although not the target of analysis, these observed patterns may relate to the identifier and set point components of the model. Specifically, they can correspond to recurrent game situations, such as defensive line coordination or *pressing triggers*, which shape player and team behaviour. These patterns act as attractors, guiding decision-making and can be systematically reinforced during training to enhance team synchronisation and tactical consistency. This type of analysis can uncover the preferred patterned behaviours of players and teams based on how they manage and control space relative to distance or angle to the goal.

In Chapter V, the results that immediately stand out concern the frequency of simplicial structures emerging in different areas of the playing field. It is important to note that the criterion established for the formation of the simplices was proximity-based criteria. In football, behaviours are highly influenced by spatial dynamics. The proximity between players often dictates passing options, defensive positioning, or offensive movements. By using proximity criteria to create simplices, these interactions are captured, enabling the identification of spatial relationships crucial to team performance (Ribeiro et al., 2019). Spatial proximity plays a key role in soccer, as it helps shape how players interact and coordinate their movements (Passos et al., 2016). This is particularly important in dynamic situations, such as rapid transitions, where positioning and spacing can determine the success of offensive and defensive actions.

When examining simplice synchronisation tendencies, the data emphasized the influence of ball possession, simplice size and type on the emergence of synchronisation tendencies. A comparison of inter-team differences in synchronisation tendencies during ball possession reveals greater variability in angle synchronisation, while distance synchronisation exhibits more statistically significant differences across playing field zones.

The observed differences between teams may reflect distinct tactics and strategies (that were not the subject of analysis in this study) tailored to the unique characteristics of their players and opposition dynamics. Although acting as a collective homeostatic system, individual players do not lose their identity. Instead, each player is singular and has her/his own characteristics, including their micro-homeostatic regulation systems, which can and should be harnessed and exploited by coaches during practice sessions as they can favour team collective behaviour. This highlights the importance of considering individualised training programs as part of their regular training sessions or as a complement to enhance aspects of individual performance that can benefit the team. For example, a team leveraging a fast winger might utilize diagonal (angle) synchronisation between midfielders and attackers to exploit spaces in wide areas. Conversely, teams with dominant aerial players might synchronise their movements vertically (distance) to target high balls in the final third.

Analysis of synchronisation tendencies in relation to simplice size has provided interesting insights. As the simplice increases, synchronisation tendencies noticeably decrease. For example, (i) in 1vs.1 situations, such as a winger engaging a fullback in a dribble, synchronisation is generally higher due to the limited number of players. In these contexts, and depending on each player characteristics and the game scenario (e.g., imbalances in defending team structure), the defender might adopt a conservative stance, aiming to delay the attacker until additional support arrives. This temporizing behaviour can increase synchronisation by maintaining a coordinated pattern of movements; however, once the defender shifts to a more aggressive approach (e.g., anti-phase behaviour), synchronisation may decrease; (ii) in 2vs.1 scenario, such as two central defenders trying to neutralize an opposing striker, synchronisation is slightly more complex, but achievable when both defensive players communicate effectively to control interpersonal distance, relational angles and space; (iii) in larger simplices, such as 3vs.3 in midfield areas, synchronisation becomes more challenging due to the increased number of interacting players and the complexity of spatial and temporal dynamics.

This observation highlights the difficulty of maintaining high synchronisation levels as the number of players involved in a performance sub-phase (e.g., attacking, defending) increases. It underscores the need for a holistic approach to understanding the game, where the collective homeostasis model plays a pivotal role.

A football team demonstrates homeostasis across multiple levels to maintain the balance between function and performance outcomes. For instance, a team`s ability to consistently maintain defensive compactness while transitioning from attack to defense reflects its macro-level homeostasis. Identifying and disrupting specific set points – key informational variables tied to tactical principles – provides insights into critical moments of play. This knowledge is highly beneficial in training, aiding in refining and adjusting behaviours across micro, meso, and macro levels. Controlling the space at the back of the defensive line is a crucial set point, as any disruption – such as a misstep by a centre-back – can create vulnerabilities and allow attackers to exploit one-on-one situations with the goalkeeper. In attacking scenarios, exploiting the half-spaces (specific field areas between the central corridor and side zones) through timely diagonal runs disrupts the opponent`s defensive set points, creating opportunities for through balls.

By analysing these data, coaches can detect players or sub-groups struggling with positional adjustments during attack or defense through delays and/or lack of synchronisation. Coaches can also assess whether specific training tasks enable players to achieve desired synchronisation levels individually and in interaction with sub-groups (sets of simplices). These insights support coaches in managing tactical nuances to enhance team synergy by fostering localized synchronisation processes.

Understanding synchronisation in football requires analysing how individual and collective behaviours adapt to specific tactical demands. The collective homeostasis model provides a comprehensive framework for examining these dynamics, with practical implications for training and task design. Integrating these insights into performance strategies allows teams to refine behaviours across micro, meso, and macro levels, improving their ability to respond adaptively to the ever-changing demands of the game.

The methodological approach proposed in this thesis emphasizes the importance of synchronisation values rooted in cooperative and opposing relationships and provides critical information about players and team dynamics. While the generalizability of these results may be limited, they present meaningful opportunities for improving team performance.

Regardless, a greater volume of data must be collected and associated with team-specific characteristics and goals to leverage this approach. For example, reduced synchronisation during a football match can sometimes be strategically advantageous, creating unpredictability, exploiting opponent disorganization, and fostering tactical creativity. By striking a balance between maintaining tactical organization and intentionally disrupting synchronisation, teams can gain a decisive edge.

Despite its limitations, this approach underscores the potential of synchronisation analysis to transform team dynamics, offering a valuable tool for advancing performance in football.

6.4 Concluding remarks

According to the findings of the studies that compiled this dissertation, the following conclusions can be outlined:

- Conceptualizing sports teams, particularly football teams, as collective homeostatic systems offer a novel perspective for understanding game dynamics, emphasizing the interplay between stability and adaptation. This model, composed of four fundamental components – players, set point, identifier, and adapter – highlights how teams self-regulate through emergent adaptive behaviours. By understanding these homeostatic adaptation processes, coaches and analysts can gain deeper insight into team evolution, optimizing training and preparation strategies.

- Emphasizing the evolutionary nature of sports performance highlights the crucial role of team preparation, training, and athlete development, rooted in the interactive regulation between the environment and the performer. This interaction involves continuous micro-level adaptations, forming an 'interaction-driven architecture' that sustains macro-level (team-level) homeostasis;

- The new methodological approach, developed to capture the continuous adaptive demands of homeostatic regulation, has identified synchronisation processes at the meso-level in competitive football successfully. The results suggest that the variables of simplice angle and distance to each goal play a crucial role in influencing players' synchronised behaviours during competitive performance;

- The results demonstrate that the proposed system exhibits a different sensitivity in detecting synchronisation tendencies compared to the traditional coordination system. While synchronisation tendencies for longitudinal and distance to the goal are similar, greater differences emerge under lateral and angular constraints;

- Findings reveal that 1vs.1, 1vs.2, and 2vs.1 structures are the most frequent, with both the type of structure and ball possession playing a significant role in synchronisation dynamics. Additionally, simplice size influences synchronisation, with larger simplices showing lower synchronisation tendencies. Understanding these system dynamics is crucial for comprehending the collective homeostasis regulation within a team, as they reflect the synergy processes that underpin effective teamwork;

- This novel method for capturing synchronisation tendencies provides coaches and performance analysts with valuable insights into the self-regulatory processes underlying team coordination. By leveraging findings from synchronisation studies, this approach enables the identification of adaptive patterns in players interactions, offering detailed information on synchronisation levels and their spatial-temporal localization. Understanding these patterns allows for the development of training methodologies that enhance collective adaptability under varying competitive conditions.

6.5 Sports teams as collective homeostatic systems…future perspectives

"*In the end, human creativity is based on life and the extraordinary fact that life comes equipped with a precise order: to resist and project into the future, no matter what happens*."

António Damásio (2017)

In addition to presenting an evolutionary perspective, the collective homeostasis model offers opportunities for reflection on several key themes for future research and practice:

a) *The importance of a communicational code – a common sporting language*. Efficient homeostatic regulation relies on clear communication and shared understanding among team members. For example, how players understand and apply concepts like attacking and defending – shaped by the language they learn – significantly influences their behaviour and performance. Research on group communication highlights how shared codes enhance synergistic interactions, enabling teams to respond more effectively to dynamic game scenarios. Indeed, the language we use profoundly shapes how we think and act.

b) *The development of a collective identity*. Sports teams operate within a *continuum* of complexity framed by three temporal dimensions: i) Past – players' histories, experiences, and learned behaviours shape their current (inter)actions; ii) Present – the "here and now" of the game demands real-time convergence of individual behaviours into a cohesive collective entity (shaped by a game model); iii) Future – goals, ambitions, and anticipatory strategies shape collective aspirations and readiness. Building a collective identity integrates these temporal dimensions, preventing disorganization in critical moments. This identity is an adaptive anchor, aligning individual actions with team objectives and enhancing readiness.

c) *Reflection on the aesthetic sense in adaptive behaviours*. The interplay between change and homeostasis reveals the aesthetic dimension of collective sports performance. This perspective invites us to consider how fluid transitions between attack and defense create moments of harmony and balance on the field. Concepts like *flow* provide a lens to explore how adaptive behaviours achieve efficiency and a sense of beauty in their execution. Investigating the aesthetics of flow dynamics deepens our appreciation of how teams achieve seamless integration in the face of evolving challenges.

d) *Capturing individual and collective attractors*. Identifying individual and collective attractors – stable patterns or states in the behaviour of player and team as a collective homeostatic system – can shed light on how teams sustain adaptive readiness. These attractors, emerging in response to various game scenarios, illuminate the dynamic interplay between attacking and defensive roles. Recognizing and analysing these attractors can foster a more cohesive and versatile team dynamic.

e) *Capturing both negative and positive feedback processes*. The ability of a team to sustain performance in dynamic and competitive environments depends on balancing regulatory processes that ensure stability while allowing for necessary adaptations. Negative feedback plays a crucial role in maintaining cohesion by counteracting disruptions and preserving the team's structural integrity. For example, defenders adjusting their positioning to neutralize emerging threats or restore defensive balance exemplifies this stabilizing function. Conversely, positive feedback facilitates structural reconfigurations that enable teams to explore new tactical possibilities. In attacking scenarios, synchronised player movements can momentarily reshape team organization, creating opportunities to exploit defensive vulnerabilities. These adaptive processes illustrate how teams dynamically regulate their structure to respond effectively to game contingencies. Attaining a balance between these feedback regulations is essential for maintaining performance adaptability. By integrating both stabilizing and adaptive regulatory processes, teams can effectively navigate competitive gameplay, demonstrating resilience in preserving identity, coherence, and flexibility.

f) *The effect of constraint manipulation on collective homeostasis development*. Examining how constraint manipulation in practice scenarios fosters both individual and collective homeostasis processes. Specifically, exploring the design of practice environments rich in shared affordances that support the development of key components of collective homeostasis model, aligned with game principles advocated by coaches.

The collective homeostasis model extends beyond a biological metaphor; it invites philosophical reflection on identity, interdependence, adaptability, and evolution. By conceptualizing sports teams as adaptive systems that mirror the organizing principles of life itself, we gain deeper insights into the nature of human creativity and cooperation. The emphasis on integration – between theory and practice, attack and defense, stability and change – aligns with the larger question of how complex systems evolve and thrive. Adopting this holistic framework enables coaches, analysts, and players to understand better the dynamics of collective adaptation, enhancing preparation and resilience in competitive contexts. This approach reflects the extraordinary order of life itself: the ability to resist, adapt, and project into the future, no matter the challenges ahead.

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Supplements: Chapter IV- Appendix A

Algorithm 1: EuclidianSimplice

Input: $S = \{a_1, \dots, a_n, b_1, \dots, b_n, g_A, g_D\}$ # List of vertices, all players from both teams, attacking and defending goals

$L = \left\{\{x_{a_1}, y_{a_1}\}, \dots, \{x_{b_n}, y_{b_n}\}, \{x_{g_A}, y_{g_A}\}, \{x_{g_D}, y_{g_D}\}\right\}$ # List of vertices' locations

Output: Σ # Set of simplices

Initialization: $Q = S$

$\Sigma = \emptyset$

$v_i : v_i \in Q$ # Initialize the current vertice, v_i

while $Q \neq \emptyset$

$Q = Q \setminus v_i$

$v_j : \min_{v_j \in S \setminus v_i} \left(d(v_i, v_j, L)\right)$ # Find the closest (d, location distance) vertice, v_j, to the current vertice, v_i

if $\exists\, \sigma_m \in \Sigma : v_i \in \sigma_m$ # Current vertice, v_i, is already in a simplice, σ_m

if $\exists\, \sigma_k \in \Sigma : v_j \in \sigma_k$ # Closest vertice, v_j, is already in a simplice, σ_k

$\sigma_n = \sigma_m \cup \sigma_k$ # Merge the two simplices σ_m and σ_k

$\Sigma = \Sigma \setminus \sigma_m$

$\Sigma = \Sigma \setminus \sigma_k$

$\Sigma = \Sigma \cup \sigma_n$

$v_i : v_i \in Q$ # Get new current vertice, v_i, not yet in a simplice

else

$\sigma_m = \sigma_m \cup v_j$ # Add closest vertice v_j to simplice σ_m

$v_i : v_i \in Q$ # Get new current vertice, v_i, not yet in a simplice

else

if $\exists\, \sigma_k \in \Sigma : v_j \in \sigma_k$ # Closest vertice, v_j, is already in a simplice, σ_k

$\sigma_k = \sigma_k \cup v_i$ # Add closest vertice v_j to simplice σ_m

$v_i : v_i \in Q$ # Get new current vertice, v_i, not yet in a simplice

else # Create new simplice, σ_n, with vertices v_i and v_j

$\sigma_n = \{v_i, v_j\}$

$Q = Q \setminus v_j$

$\Sigma = \Sigma \cup \sigma_n$

$v_i = v_j$

Table 4. Permutation Test and Brunner-Munzel Statistic for Lateral orientation on field (y-axis) and Angle to the Attacked Goal

Lat	Long	Mean difference		Rank difference		
		d	p	W	df	p
LFT2	DEF1					
	DEF2	0.172	< .001**	6.5	163	< .001**
	MID1	0.059	< .001**	8.6	1050	< .001**
	MID2	0.016	0.004*	2.4	1331	0.018*
	ATT2	-0.029	< .001**	-5.0	794	< .001**
	ATT1	-0.046	< .001**	-7.4	166	< .001**
LFT1	DEF1	0.017	0.795	0.4	76	0.719
	DEF2	0.033	0.058	2.1	621	0.040*
	MID1	0.029	0.010*	2.2	1737	0.030*
	MID2	0.015	0.090	0.4	2062	0.659
	ATT2	-0.036	0.004*	-4.1	1310	< .001**
	ATT1	-0.105	< .001**	-4.7	429	< .001**
RGT1	DEF1	-0.007	0.877	0.3	113	0.772
	DEF2	0.014	0.459	1.1	659	0.288
	MID1	0.007	0.486	0.8	1576	0.446
	MID2	0.002	0.807	0.0	2158	0.998
	ATT2	-0.045	0.001*	-3.9	1222	<.001**
	ATT1	-0.150	<.001**	-6.7	410	<.001**
RGT2	DEF1	0.169	<.001**	4.9	80	<.001**
	DEF2	0.119	<.001**	7.6	286	<.001**
	MID1	0.039	<.001**	5.0	648	<.001**
	MID2	0.005	0.320	0.7	1159	0.505
	ATT2	-0.030	<.001**	-4.6	502	<.001**
	ATT1	-0.063	<.001**	-5.1	45	<.001**

Significance level: p<0.05 *; p<0.01**

Blank spaces in the table indicate that differences are not presented when either of the two comparison groups has fewer than 10 samples.

Table 5. Permutation Test and Brunner-Munzel Statistic for Lateral orientation on field (y-axis) and Angle to the Defended Goal

Lat	Long	Mean difference		Rank difference		
		d	p	W	df	p
LFT2	DEF1					
	DEF2	-0.010	0.279	-1.7	186	0.090
	MID1	-0.001	0.844	1.2	1051	0.213
	MID2	0.043	<.001**	6.7	1263	<.001**
	ATT2	0.136	<.001**	11.1	710	<.001**
	ATT1	0.158	<.001**	6.7	146	<.001**
LFT1	DEF1	-0.227	<.001**	-3.7	57	<.001**
	DEF2	-0.008	0.630	-1.7	619	0.084
	MID1	-0.013	0.205	-0.7	1737	0.489
	MID2	0.010	0.230	1.4	2080	0.168
	ATT2	0.039	0.002*	3.0	1311	0.002*
	ATT1	0.001	0.976	0.4	428	0.677
RGT1	DEF1	-0.079	0.084	-1.6	111	0.124
	DEF2	-0.027	0.142	-2.7	649	0.006*
	MID1	0.020	0.077	1.3	1576	0.180
	MID2	0.016	0.084	1.6	2160	0.105
	ATT2	0.031	0.028*	3.2	1205	0.001*
	ATT1	0.044	0.096	1.7	415	0.081
RGT2	DEF1	-0.031	<.001**	-4.0	83	<.001**
	DEF2	-0.022	0.001*	-2.9	313	0.004*
	MID1	0.021	0.003*	2.4	688	0.017*
	MID2	0.051	<.001**	8.6	1155	<.001**
	ATT2	0.150	<.001**	8.9	450	<.001**
	ATT1	0.341	<.001**	5.2	36	<.001**

Significance level: p<0.05 *; p<0.01**

Blank spaces in the table indicate that differences are not presented when either of the two comparison groups has fewer than 10 samples.

Table 6. Permutation Test and Brunner-Munzel Statistic for Longitudinal (x-axis) orientation on field and Distance to the Attacked Goal

Lat	Long	Mean difference		Rank difference		
		d	p	W	df	p
LFT2	DEF1					
	DEF2	-0.004	0.218	-0.7	186	0.497
	MID1	0.002	0.818	-0.2	1056	0.821
	MID2	0.018	0.021*	2.5	1331	0.012*
	ATT2	0.020	<.001**	6.5	786	<.001**
	ATT1	0.004	0.007*	1.9	174	0.055
LFT1	DEF1	-0.000	0.933	-0.1	76	0.902
	DEF2	0.001	0.709	0.2	622	0.824
	MID1	0.003	0.684	0.4	1740	0.683
	MID2	-0.001	0.903	0.8	2071	0.403
	ATT2	0.001	0.176	3.2	1312	0.001*
	ATT1	0.008	0.136	2.0	426	0.042*
RGT1	DEF1	-0.001	0.909	-0.8	113	0.453
	DEF2	0.000	0.882	-0.4	654	0.694
	MID1	0.001	0.942	0.5	1580	0.644
	MID2	0.003	0.666	-0.2	2155	0.852
	ATT2	0.000	0.833	0.9	1219	0.347
	ATT1	0.001	0.083	1.6	415	0.114
RGT2	DEF1	-0.000	0.959	0.0	88	0.971
	DEF2	-0.001	0.819	0.0	314	0.988
	MID1	-0.006	0.654	-0.4	686	0.679
	MID2	0.021	0.010*	1.6	1154	0.103
	ATT2	0.013	<.001**	2.5	504	0.013*
	ATT1	0.012	0.027*	3.4	64	0.001*

Significance level: p<0.05 *; p<0.01**

Blank spaces in the table indicate that differences are not presented when either of the two comparison groups has fewer than 10 samples.

Table 7. Permutation Test and Brunner-Munzel Statistic for Longitudinal (x-axis) orientation on field and Distance to the Defended Goal

Lat	Long	Mean difference		Rank difference		
		d	p	W	df	p
LFT2	DEF1					
	DEF2	0.033	<.001**	2.8	176	0.005*
	MID1	0.015	0.121	1.8	1055	0.065
	MID2	-0.007	0.246	0.8	1320	0.426
	ATT2	-0.001	0.500	-0.4	793	0.691
	ATT1	-0.001	0.501	-0.3	173	0.794
LFT1	DEF1	0.003	0.433	0.5	75	0.619
	DEF2	0.004	0.117	1.1	621	0.285
	MID1	-0.002	0.773	0.8	1739	0.418
	MID2	0.003	0.647	1.3	2080	0.179
	ATT2	0.002	0.163	0.7	1313	0.490
	ATT1	-0.000	0.842	-0.1	430	0.939
RGT1	DEF1	0.003	0.578	2.1	114	0.035*
	DEF2	0.003	0.256	1.3	659	0.190
	MID1	0.011	0.180	1.4	1578	0.152
	MID2	0.002	0.725	0.3	2154	0.775
	ATT2	0.002	0.133	1.3	1222	0.208
	ATT1	0.000	0.646	0.7	416	0.487
RGT2	DEF1	0.005	0.011*	2.8	80	0.006*
	DEF2	0.008	0.017*	3.5	312	<.001**
	MID1	0.010	0.483	1.2	687	0.241
	MID2	-0.004	0.568	-0.2	1159	0.870
	ATT2	-0.001	0.628	0.0	508	0.994
	ATT1	-0.002	0.608	-0.6	55	0.559

Significance level: $p<0.05$ *; $p<0.01$**

Blank spaces in the table indicate that differences are not presented when either of the two comparison groups has fewer than 10 samples.

Table 8. Permutation Test and Brunner-Munzel Statistic for Angle to the Attacked Goal – Possession: Team A vs. Team B

Lat	Long	Mean difference		Rank difference		
		d	p	W	df	p
LFT2	DEF1					
	DEF2	0,171	< .001**	3,4	92	0.001*
	MID1	-0,005	0.763	-0,4	440	0.669
	MID2	-0,016	0.101	-2,8	298	0.006*
	ATT2	-0,039	< .001**	-7,1	291	< .001**
	ATT1	0,007	0.120	1,2	77	0.251
LFT1	DEF1	-0,198	0.038*	-2,4	25	0.025*
	DEF2	0,009	0.726	-0,7	288	0.513
	MID1	0,031	0.060	0,8	810	0.405
	MID2	-0,056	< .001**	-5,2	825	< .001**
	ATT2	-0,027	0.119	-1,8	476	0.075
	ATT1	-0,012	0.693	0,2	213	0.805
RGT1	DEF1	-0,052	0.420	-0,5	48	0.605
	DEF2	0,085	0.001*	4,5	308	< .001**
	MID1	0,043	0.003*	2,8	756	0.005*
	MID2	-0,01	0.446	-1,6	789	0.111
	ATT2	0,038	0.043*	-0,1	373	0.888
	ATT1	0,044	0.186	-0,1	206	0.910
RGT2	DEF1	-0,238	0.004*	-3,4	42	0.001*
	DEF2	-0,055	0.129	-1,9	82	0.057
	MID1	0,016	0.204	1,9	336	0.059
	MID2	-0,004	0.664	-2,1	425	0.039*
	ATT2	0,007	0.171	0,5	188	0.631
	ATT1	0,008	0.626	-1,2	19	0.260

Significance level: p<0.05 *; p<0.01**

Blank spaces in the table indicate that differences are not presented when either of the two comparison groups has fewer than 10 samples.

Table 9. Permutation Test and Brunner-Munzel Statistic for Distance to the Attacked Goal – Possession: Team A vs. Team B

Lat	Long	Mean difference		Rank difference		
		d	p	W	df	p
LFT2	DEF1					
	DEF2	-0,01	0.017*	-2,5	88	0.015*
	MID1	-0,028	0.036*	-3,4	388	< .001**
	MID2	0,001	0.903	-2,2	238	0.027*
	ATT2	-0,028	< .001**	-4,8	238	< .001**
	ATT1	-0,003	0.276	-2,5	66	0.013*
LFT1	DEF1	-0,003	0.458	0,7	35	0.519
	DEF2	-0,003	0.373	-1,1	268	0.276
	MID1	0,007	0.564	-2,2	798	0.030*
	MID2	-0,004	0.621	-5,4	647	< .001**
	ATT2	-0,002	0.343	1,4	566	0.160
	ATT1	-0,018	< .001**	-4,1	213	< .001**
RGT1	DEF1	0,014	0.047*	2,9	54	0.006*
	DEF2	-0,001	0.810	-0,8	301	0.450
	MID1	0,002	0.838	-0,8	782	0.420
	MID2	-0,02	0.035*	-2,3	844	0.024*
	ATT2	-0,006	0.006*	-3,4	466	< .001**
	ATT1	-0,001	0.517	-0,3	188	0.766
RGT2	DEF1	0,003	0.046*	2,4	42	0.019*
	DEF2	0,006	0.257	1,9	56	0.062
	MID1	-0,03	0.138	-0,8	289	0.430
	MID2	0,018	0.189	0,4	459	0.710
	ATT2	-0,008	0.304	-1,5	192	0.125
	ATT1	0,004	0.802	1,7	31	0.090

Significance level: $p<0.05$ *; $p<0.01$**

Blank spaces in the table indicate that differences are not presented when either of the two comparison groups has fewer than 10 samples.

Appendix B

Angle to defended goal, d_{DG}, Possession Team A

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2		0.973	0.958	0.901	0.806	0.843
LFT1	0.834	0.836	0.874	0.828	0.740	0.800
RGT1	0.858	0.882	0.862	0.825	0.743	0.648
RGT2	0.981	0.971	0.952	0.907	0.804	0.588

Angle to defended goal, d_{DG}, Possession Team B

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2	0.996	0.945	0.957	0.896	0.738	0.702
LFT1	0.920	0.888	0.826	0.879	0.818	0.629
RGT1	0.838	0.777	0.768	0.844	0.769	0.537
RGT2	0.989	0.969	0.927	0.874	0.773	0.566

Angle to defended goal, d_{AG}, Difference Team A vs. Team B

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2		0.027, p=0.033* W=0.6,df=68,p=0.531	0.001, p=0.874 W=-0.3,df=400,p=0.774	0.006, p=0.611 W=-1.1,df=240,p=0.254	0.068, p=0.004* W=1.8,df=171,p=0.072	0.142, p=0.004* W=1.7,df=77,p=0.092
LFT1	-0.086, p=0.114 W=-1.0,df=36,p=0.331	-0.052, p=0.037* W=-2.4,df=293,p=0.015*	0.047, p=0.001* W=2.1,df=752,p=0.036*	-0.051, p<.001** W=-4.7,df=790,p<.001**	-0.078, p<.001** W=-4.4,df=476,p<.001**	0.171, p<.001** W=4.0,df=172,p<.001**
RGT1	0.020, p=0.703 W=0.4,df=54,p=0.682	0.104, p<.001** W=4.4,df=327,p<.001**	0.093, p<.001** W=5.9,df=751,p<.001**	-0.018, p=0.197 W=-1.4,df=835,p=0.160	-0.026, p=0.207 W=-1.3,df=471,p=0.202	0.111, p=0.005* W=2.7,df=199,p=0.007*
RGT2	-0.009, p=0.283 W=0.4,df=39,p=0.708	0.002, p=0.844 W=1.5,df=55,p=0.138	0.025, p=0.046* W=0.2,df=343,p=0.824	0.033, p=0.010* W=0.7,df=371,p=0.454	0.030, p=0.334 W=1.4,df=231,p=0.168	0.022, p=0.825 W=0.1,df=24,p=0.892

Distance to defended goal, d_{DG}, Possession Team A

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2		0.926	0.902	0.949	0.984	0.994
LFT1	0.987	0.974	0.916	0.918	0.986	0.993
RGT1	0.992	0.983	0.888	0.916	0.980	0.994
RGT2	0.994	0.976	0.887	0.943	0.978	0.994

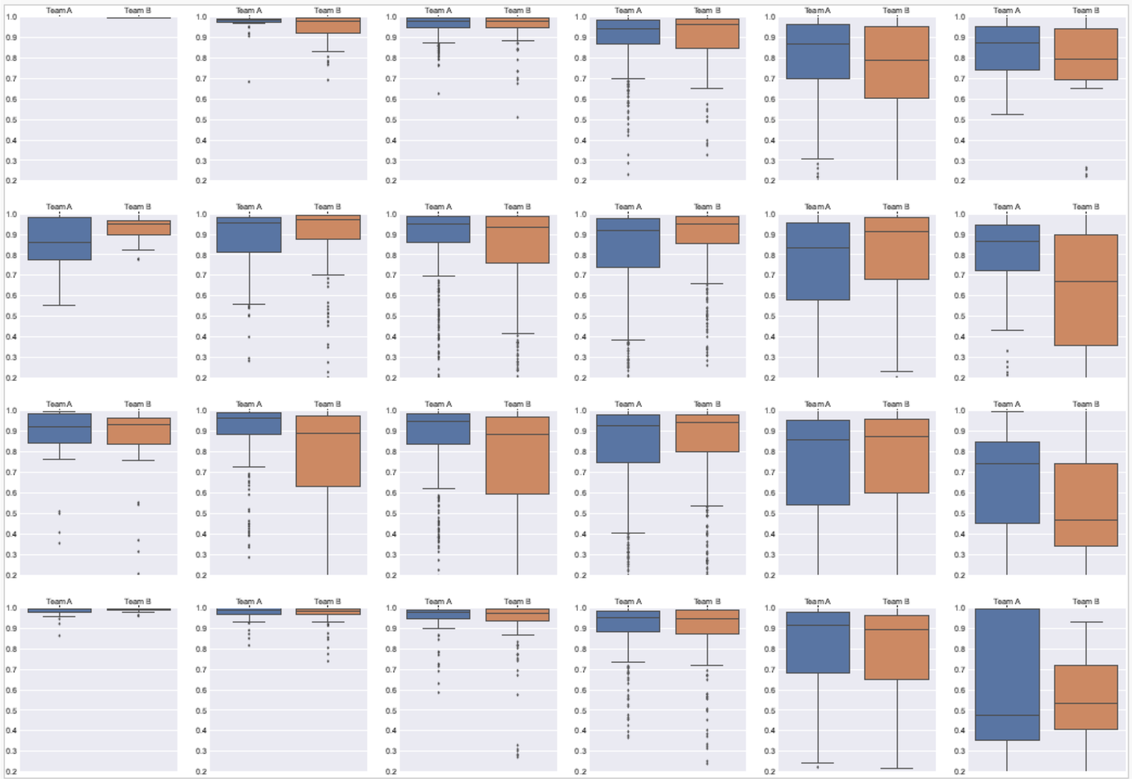
Distance to defended goal, d_{DG}, Possession Team B

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2	0.999	0.960	0.923	0.946	0.994	0.994
LFT1	0.993	0.976	0.917	0.957	0.986	0.994
RGT1	0.977	0.980	0.922	0.940	0.985	0.997
RGT2	0.986	0.973	0.906	0.941	0.984	0.989

Distance to attacked goal, d_{AG}, Difference Team A vs. Team B

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2		-0.034, p=0.037* W=-2.7,df=91,p=0.008*	-0.020, p=0.171 W=-1.6,df=402,p=0.100	0.003, p=0.766 W=-3.2,df=256,p=0.002*	-0.010, p<.001** W=-5.6,df=239,p<.001**	-0.001, p=0.606 W=-1.4,df=73,p=0.178
LFT1	-0.006, p=0.299 W=1.9,df=35,p=0.060	-0.003, p=0.491 W=-1.7,df=272,p=0.081	-0.000, p=0.989 W=-1.8,df=830,p=0.074	-0.039, p<.001** W=-8.6,df=696,p<.001**	-0.000, p=0.836 W=1.5,df=502,p=0.126	-0.002, p=0.231 W=-2.0,df=211,p=0.051
RGT1	0.015, p=0.015* W=2.0,df=56,p=0.051	0.003, p=0.449 W=0.2,df=326,p=0.816	-0.034, p=0.006* W=-2.9,df=789,p=0.004*	-0.024, p=0.009* W=-3.1,df=900,p=0.002*	-0.006, p=0.013* W=-1.6,df=453,p=0.104	-0.002, p=0.005* W=-1.7,df=154,p=0.087
RGT2	0.009, p=0.007* W=2.4,df=32,p=0.023*	0.003, p=0.587 W=1.7,df=55,p=0.101	-0.019, p=0.361 W=1.3,df=273,p=0.182	0.002, p=0.832 W=2.4,df=533,p=0.016*	-0.006, p=0.094 W=-1.2,df=208,p=0.224	0.005, p=0.354 W=4.9,df=31,p<.001**

Box plot angle to defended goal (ball possession)



Box plot distance to defended goal (ball possession)

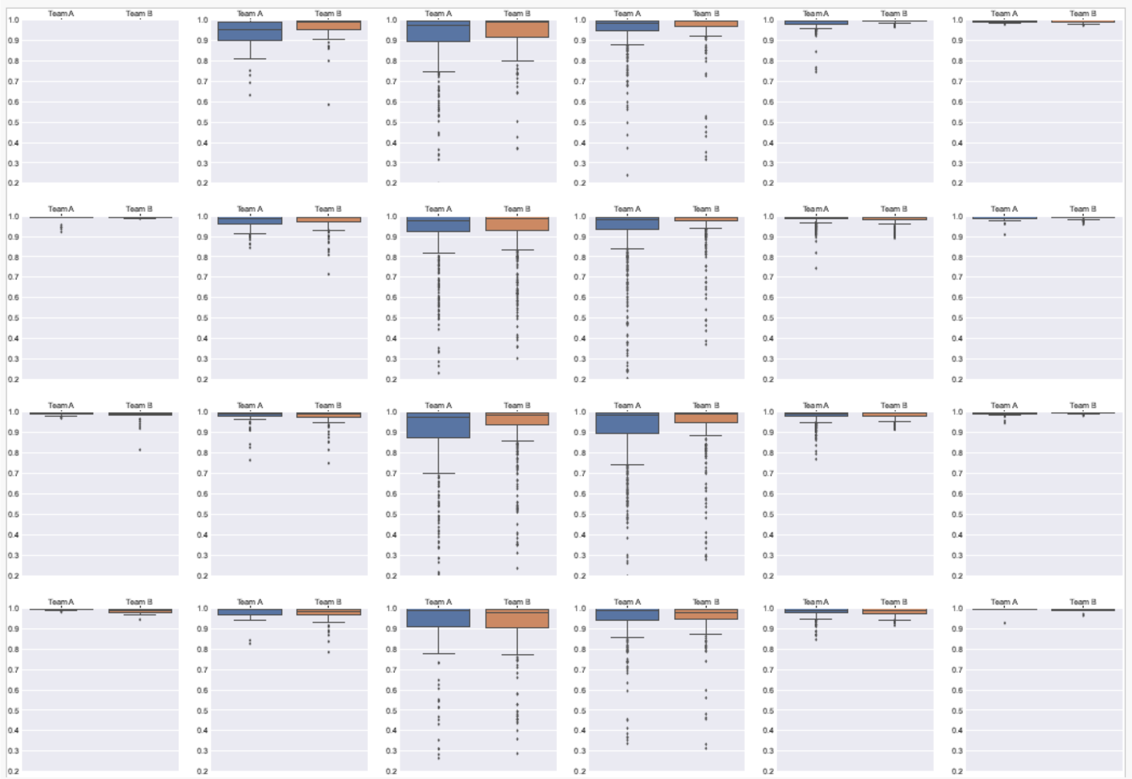


Table 10. Permutation Test and Brunner-Munzel Statistic for Angle to the Defended Goal – Simplice Size 2-3

Lat	Long	Mean difference		Rank difference		
		d	p	W	df	p
LFT2	DEF1					
	DEF2	-0.017	0.302	1.6	49	0.127
	MID1	0.018	0.004*	6.2	268	< .001**
	MID2	0.053	< .001**	6.8	385	< .001**
	ATT2	0.030	0.208	2.8	295	0.005*
	ATT1	-0.106	0.082	-0.8	58	0.429
LFT1	DEF1	-0.017	0.780	-0.0	22	0.964
	DEF2	-0.046	0.111	1.2	219	0.233
	MID1	0.045	0.012*	6.1	582	< .001**
	MID2	0.009	0.523	1.8	708	0.075
	ATT2	0.037	0.099	2.6	429	0.009*
	ATT1	0.145	< .001**	4.0	152	< .001**
RGT1	DEF1	0.054	0.156	1.6	31	0.123
	DEF2	0.048	0.135	4.8	210	< .001**
	MID1	0.017	0.410	2.5	516	0.013*
	MID2	-0.007	0.643	2.5	714	0.012*
	ATT2	-0.005	0.864	-0.3	402	0.783
	ATT1	0.160	< .001**	4.3	124	< .001**
RGT2	DEF1	0.008	0.430	0.8	23	0.426
	DEF2	0.015	0.094	1.7	85	0.102
	MID1	-0.013	0.471	2.0	164	0.048*
	MID2	-0.000	0.985	2.1	272	0.036*
	ATT2	0.054	0.191	1.7	76	0.102
	ATT1					

Significance level: p<0.05 *; p<0.01**

Blank spaces in the table indicate that differences are not presented when either of the two comparison groups has fewer than 10 samples.

Table 11. Permutation Test and Brunner-Munzel Statistic for Angle to the Defended Goal – Simplice Size 2-5

Lat	Long	Mean difference		Rank difference		
		d	p	W	df	p
LFT2	DEF1					
	DEF2					
	MID1	0.030	0.050*	4.9	21	< .001**
	MID2	0.105	< .001**	7.9	98	< .001**
	ATT2	0.138	0.013*	2.8	28	0.010*
	ATT1					
LFT1	DEF1					
	DEF2	-0.011	0.900	3.0	64	0.004*
	MID1	0.034	0.155	6.6	221	< .001**
	MID2	0.075	< .001**	6.5	174	< .001**
	ATT2	0.061	0.072	4.9	174	< .001**
	ATT1	0.255	0.002*	4.3	17	< .001**
RGT1	DEF1					
	DEF2	0.003	0.913	4.7	133	< .001**
	MID1	-0.003	0.958	1.6	107	0.124
	MID2	0.105	< .001**	7.6	237	< .001**
	ATT2	0.073	0.071	2.5	88	0.015*
	ATT1	0.207	0.003*	4.4	68	< .001**
RGT2	DEF1					
	DEF2					
	MID1	0.004	0.822	3.8	23	< .001**
	MID2	0.002	0.877	2.2	64	0.029*
	ATT2					
	ATT1					

Significance level: p<0.05 *; p<0.01**

Blank spaces in the table indicate that differences are not presented when either of the two comparison groups has fewer than 10 samples.

Table 12. Permutation Test and Brunner-Munzel Statistic for Angle to the Defended Goal – Simplice Size 3-5

Lat	Long	Mean difference		Rank difference		
		d	p	W	df	p
LFT2	DEF1					
	DEF2					
	MID1	0.012	0.360	1.3	22	0.214
	MID2	0.052	0.013*	2.1	105	0.041*
	ATT2	0.109	0.023*	1.2	25	0.254
	ATT1					
LFT1	DEF1					
	DEF2	0.035	0.327	1.5	37	0.138
	MID1	-0.010	0.672	1.0	194	0.306
	MID2	0.066	0.004*	5.0	169	<.001**
	ATT2	0.024	0.462	2.2	173	0.026*
	ATT1	0.111	0.189	1.7	18	0.116
RGT1	DEF1					
	DEF2	-0.045	0.399	0.2	58	0.821
	MID1	-0.020	0.536	-0.2	101	0.811
	MID2	0.113	<.001**	6.0	192	<.001**
	ATT2	0.078	0.036*	2.1	90	0.037*
	ATT1	0.047	0.420	0.2	61	0.875
RGT2	DEF1					
	DEF2					
	MID1	0.017	0.372	1.9	32	0.064
	MID2	0.002	0.887	0.5	70	0.585
	ATT2					
	ATT1					

Significance level: $p<0.05$ *; $p<0.01$**

Blank spaces in the table indicate that differences are not presented when either of the two comparison groups has fewer than 10 samples.

Table 13. Permutation Test and Brunner-Munzel Statistic for Distance to the Defended Goal – Simplice Size 2-3

Lat	Long	Mean difference		Rank difference		
		d	p	W	df	p
LFT2	DEF1					
	DEF2	0.028	0.150	3.5	55	<0.001**
	MID1	0.074	<0.001**	7.6	269	<0.001**
	MID2	0.042	<0.001**	5.7	405	<0.001**
	ATT2	0.012	<0.001**	5.1	263	<0.001**
	ATT1	-0.002	0.242	0.1	62	0.925
LFT1	DEF1	0.020	0.027*	1.9	13	0.081
	DEF2	0.012	0.019*	3.7	225	<0.001**
	MID1	0.016	0.119	4.3	581	<0.001**
	MID2	-0.002	0.853	4.0	685	<0.001**
	ATT2	0.002	0.175	4.1	438	<0.001**
	ATT1	-0.000	0.850	1.2	147	0.219
RGT1	DEF1	-0.013	0.112	-1.7	33	0.091
	DEF2	0.010	0.011*	5.2	223	<0.001**
	MID1	-0.008	0.599	3.2	508	0.002*
	MID2	0.013	0.140	5.3	723	<0.001**
	ATT2	0.006	0.024*	6.0	369	<0.001**
	ATT1	0.003	0.002*	3.8	130	<0.001**
RGT2	DEF1	0.013	<0.001**	2.9	11	0.013*
	DEF2	0.015	0.026*	2.3	100	0.025*
	MID1	0.071	0.006*	5.7	166	<0.001**
	MID2	0.031	0.007*	6.6	262	<0.001**
	ATT2	0.009	0.017*	3.4	75	0.001*
	ATT1					

Significance level: p<0.05 *; p<0.01**

Blank spaces in the table indicate that differences are not presented when either of the two comparison groups has fewer than 10 samples.

Table 14. Permutation Test and Brunner-Munzel Statistic for Distance to the Defended Goal – Simplice Size 2-5

Lat	Long	Mean difference		Rank difference		
		d	p	W	df	p
LFT2	DEF1					
	DEF2					
	MID1	0.008	0.726	5.6	29	<0.001**
	MID2	0.051	0.001*	7.4	98	<0.001**
	ATT2	0.009	0.048*	5.0	36	<0.001**
	ATT1					
LFT1	DEF1					
	DEF2	0.020	0.017*	6.8	68	<0.001**
	MID1	0.110	<0.001**	9.5	163	<0.001**
	MID2	0.092	<0.001**	10.2	169	<0.001**
	ATT2	0.014	<0.001**	8.7	125	<0.001**
	ATT1	0.004	0.281	2.8	21	0.010*
RGT1	DEF1					
	DEF2	0.013	0.024*	4.8	34	<0.001**
	MID1	0.039	0.152	6.7	147	<0.001**
	MID2	0.101	<0.001**	11.7	217	<0.001**
	ATT2	0.014	0.001*	7.7	133	<0.001**
	ATT1	0.004	0.009*	5.3	50	<0.001**
RGT2	DEF1					
	DEF2					
	MID1	0.021	0.569	4.5	24	<0.001**
	MID2	0.048	0.011*	5.2	70	<0.001**
	ATT2					
	ATT1					

Significance level: p<0.05 *; p<0.01**

Blank spaces in the table indicate that differences are not presented when either of the two comparison groups has fewer than 10 samples.

Table 15. Permutation Test and Brunner-Munzel Statistic for Distance to the Defended Goal – Simplice Size 3-5

Lat	Long	Mean difference		Rank difference		
		d	p	W	df	p
LFT2	DEF1					
	DEF2					
	MID1	-0.067	0.147	-0.1	39	0.954
	MID2	0.010	0.629	2.5	118	0.014*
	ATT2	-0.003	0.928	1.1	38	0.294
	ATT1					
LFT1	DEF1					
	DEF2	0.008	0.418	2.7	64	0.010*
	MID1	0.094	<0.001**	5.5	159	<0.001**
	MID2	0.094	<0.001**	6.9	131	<0.001**
	ATT2	0.011	<0.001**	5.0	107	<0.001**
	ATT1	0.005	0.074	1.9	18	0.072
RGT1	DEF1					
	DEF2	0.002	0.712	2.1	36	0.045*
	MID1	0.048	0.046*	4.4	114	<0.001**
	MID2	0.089	<0.001**	6.9	192	<0.001**
	ATT2	0.007	0.148	2.8	91	0.006*
	ATT1	0.001	0.591	1.6	56	0.125
RGT2	DEF1					
	DEF2					
	MID1	-0.050	0.375	0.2	33	0.832
	MID2	0.017	0.480	-0.1	71	0.904
	ATT2					
	ATT1					

Significance level: p<0.05 *; p<0.01**

Blank spaces in the table indicate that differences are not presented when either of the two comparison groups has fewer than 10 samples.

Appendix C

Angle to attacked goal, d_{AG}, Size 2

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2		0.732	0.909	0.942	0.967	0.982
LFT1	0.675	0.851	0.850	0.867	0.893	0.932
RGT1	0.837	0.819	0.854	0.875	0.845	0.856
RGT2	0.774	0.854	0.927	0.948	0.982	0.975

Angle to attacked goal, d_{AG}, Size 3

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2	0.984	0.886	0.875	0.923	0.939	0.992
LFT1	0.649	0.826	0.807	0.861	0.839	0.831
RGT1	0.812	0.760	0.834	0.873	0.859	0.718
RGT2	0.870	0.843	0.920	0.958	0.973	0.982

Angle to attacked goal, d_{AG}, Size 5

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2		0.724	0.903	0.899	0.916	0.971
LFT1	0.511	0.802	0.782	0.795	0.818	0.757
RGT1	0.681	0.838	0.822	0.770	0.779	0.788
RGT2		0.870	0.917	0.928	0.969	0.988

Angle to attacked goal, d_{AG}, Difference Size 2 vs. Size 3

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2			0.030, p=0.045* W=4.9,df=21,p<.001**	0.105, p<.001** W=7.9,df=98,p<.001**	0.138, p=0.009* W=2.8,df=28,p=0.010*	
LFT1		-0.011, p=0.887 W=3.0,df=64,p=0.004*	0.034, p=0.159 W=6.6,df=221,p<.001**	0.075, p=0.002* W=6.5,df=174,p<.001**	0.061, p=0.060 W=4.9,df=174,p<.001**	0.255, p=0.002* W=4.3,df=17,p<.001**
RGT1		0.003, p=0.911 W=4.7,df=133,p<.001**	-0.003, p=0.975 W=1.6,df=107,p=0.124	0.105, p<.001** W=7.6,df=237,p<.001**	0.073, p=0.066 W=2.5,df=88,p=0.015*	0.207, p=0.003* W=4.4,df=68,p<.001**
RGT2			0.004, p=0.836 W=3.8,df=23,p<.001**	0.002, p=0.886 W=2.2,df=64,p=0.029*		

Angle to attacked goal, d_{AG}, Difference Size 2 vs. Size 5

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2			0.005, p=0.812 W=2.6,df=21,p=0.016*	0.043, p=0.014* W=6.9,df=106,p<.001**	0.051, p=0.001* W=8.0,df=57,p<.001**	
LFT1		0.050, p=0.313 W=2.0,df=40,p=0.048*	0.068, p=0.024* W=7.5,df=254,p<.001**	0.072, p=0.011* W=7.1,df=193,p<.001**	0.075, p=0.009* W=4.3,df=93,p<.001**	0.176, p<.001** W=2.9,df=14,p=0.013*
RGT1		-0.019, p=0.782 W=2.9,df=64,p=0.005*	0.033, p=0.289 W=3.3,df=113,p=0.001*	0.105, p<.001** W=8.5,df=241,p<.001**	0.065, p=0.058 W=3.2,df=98,p=0.002*	0.068, p=0.232 W=2.0,df=44,p=0.054
RGT2			0.010, p=0.679 W=2.4,df=19,p=0.028*	0.020, p=0.217 W=5.1,df=67,p<.001**		

Angle to defended goal, d_{AG}, Difference Size 3 vs. Size 5

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2			0.012, p=0.380 W=1.3,df=22,p=0.214	0.052, p=0.016* W=2.1,df=105,p=0.041*	0.109, p=0.023* W=1.2,df=25,p=0.254	
LFT1		0.035, p=0.332 W=1.5,df=37,p=0.138	-0.010, p=0.667 W=1.0,df=194,p=0.306	0.066, p=0.003* W=5.0,df=169,p<.001**	0.024, p=0.457 W=2.2,df=173,p=0.026*	0.111, p=0.184 W=1.7,df=18,p=0.116
RGT1		-0.045, p=0.384 W=0.2,df=58,p=0.821	-0.020, p=0.524 W=-0.2,df=101,p=0.811	0.113, p<.001** W=6.0,df=192,p<.001**	0.078, p=0.041* W=2.1,df=90,p=0.037*	0.047, p=0.412 W=0.2,df=61,p=0.875
RGT2			0.017, p=0.381 W=1.9,df=32,p=0.064	0.002, p=0.897 W=0.5,df=70,p=0.585		

Distance to attacked goal, d_{AG}, Size 2

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2		0.988	0.948	0.948	0.967	0.990
LFT1	0.995	0.981	0.930	0.955	0.991	0.972
RGT1	0.986	0.990	0.951	0.958	0.986	0.997
RGT2	0.996	0.989	0.925	0.949	0.973	0.985

Distance to attacked goal, d_{AG},, Size 3

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2	0.999	0.977	0.904	0.905	0.963	0.990
LFT1	0.983	0.981	0.930	0.944	0.985	0.994
RGT1	0.997	0.982	0.907	0.934	0.985	0.995
RGT2	0.995	0.978	0.911	0.895	0.961	0.974

Distance to attacked goal, d_{AG},, Size 5

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2		0.975	0.913	0.865	0.937	0.987
LFT1	0.996	0.958	0.867	0.879	0.979	0.990
RGT1	0.984	0.974	0.882	0.865	0.976	0.989
RGT2		0.984	0.901	0.908	0.960	0.981

Distance to defended goal, d_{AG}, Difference Size 2 vs. Size 3

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2		0.028, p=0.150 W=3.5,df=55,p<.001**	0.074, p<.001** W=7.6,df=269,p<.001**	0.042, p<.001** W=5.7,df=405,p<.001**	0.012, p<.001** W=5.1,df=263,p<.001**	-0.002, p=0.242 W=0.1,df=62,p=0.925
LFT1	0.020, p=0.027* W=1.9,df=13,p=0.081	0.012, p=0.019* W=3.7,df=225,p<.001**	0.016, p=0.119 W=4.3,df=581,p<.001**	-0.002, p=0.853 W=4.0,df=685,p<.001**	0.002, p=0.175 W=4.1,df=438,p<.001**	-0.000, p=0.850 W=1.2,df=147,p=0.219
RGT1	-0.013, p=0.112 W=-1.7,df=33,p=0.091	0.010, p=0.011* W=5.2,df=223,p<.001**	-0.008, p=0.599 W=3.2,df=508,p=0.002*	0.013, p=0.140 W=5.3,df=723,p<.001**	0.006, p=0.024* W=6.0,df=369,p<.001**	0.003, p=0.002* W=3.8,df=130,p<.001**
RGT2	0.013, p<.001** W=2.9,df=11,p=0.013*	0.015, p=0.026* W=2.3,df=100,p=0.025*	0.071, p=0.006* W=5.7,df=166,p<.001**	0.031, p=0.007* W=6.6,df=262,p<.001**	0.009, p=0.017* W=3.4,df=75,p=0.001*	

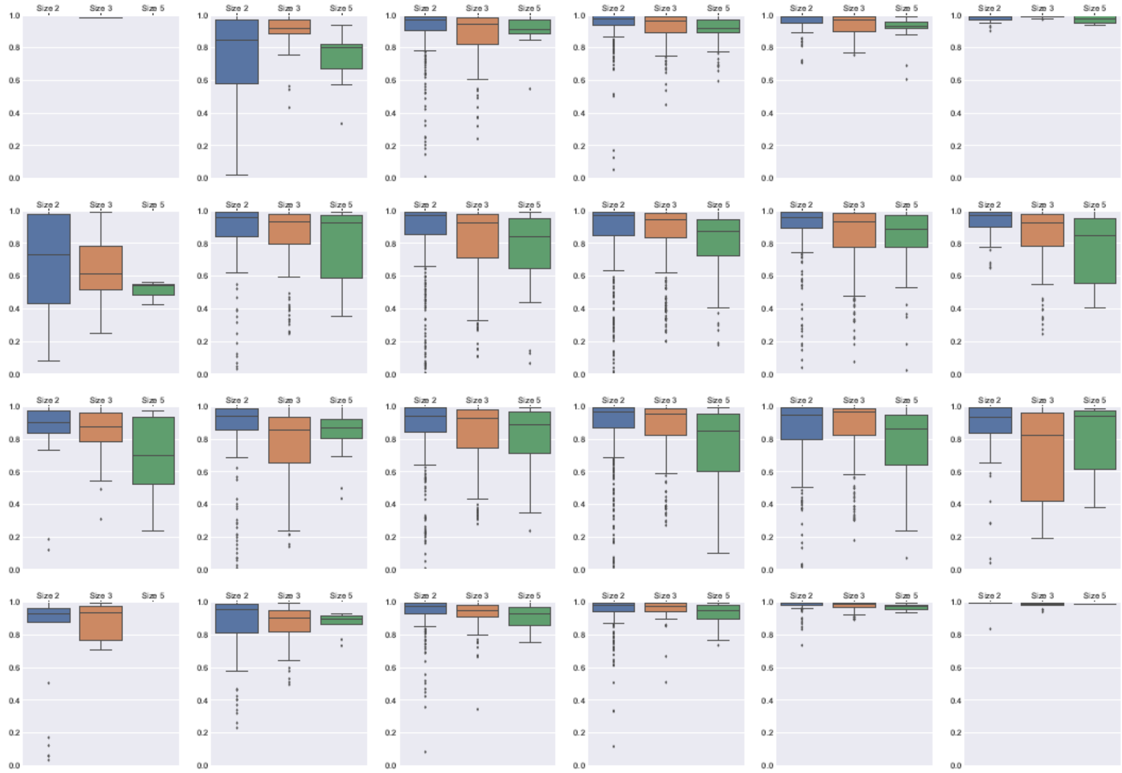
Distance to attacked goal, d_{AG}, Difference Size 2 vs. Size 5

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2			0.035, p=0.297 W=7.0,df=25,p<.001**	0.083, p<.001** W=6.1,df=101,p<.001**	0.030, p=0.256 W=4.7,df=36,p<.001**	
LFT1		0.022, p=0.028* W=7.6,df=71,p<.001**	0.062, p=0.008* W=10.6,df=279,p<.001**	0.076, p<.001** W=11.2,df=175,p<.001**	0.012, p<.001** W=9.1,df=102,p<.001**	-0.018, p=0.805 W=3.3,df=31,p=0.003*
RGT1		0.015, p=0.020* W=7.3,df=64,p<.001**	0.070, p=0.001* W=7.3,df=113,p<.001**	0.093, p<.001** W=16.5,df=311,p<.001**	0.010, p=0.043* W=6.6,df=141,p<.001**	0.009, p<.001** W=6.4,df=44,p<.001**
RGT2			0.024, p=0.550 W=2.5,df=20,p=0.019*	0.041, p=0.067 W=5.4,df=87,p<.001**		

Distance to attacked goal, d_{AG}, Difference Size 3 vs. Size 5

	DEF3	DEF2	DEF1	ATT1	ATT2	ATT3
LFT2			-0.008, p=0.852 W=1.0,df=28,p=0.341	0.040, p=0.134 W=1.2,df=98,p=0.248	0.026, p=0.167 W=1.9,df=40,p=0.071	
LFT1		0.022, p<.001** W=4.7,df=42,p<.001**	0.063, p=0.005* W=7.1,df=218,p<.001**	0.065, p<.001** W=7.0,df=147,p<.001**	0.006, p=0.058 W=4.6,df=110,p<.001**	0.004, p=0.046* W=3.0,df=18,p=0.009*
RGT1		0.008, p=0.148 W=1.5,df=37,p=0.132	0.026, p=0.325 W=3.5,df=117,p<.001**	0.068, p<.001** W=6.8,df=232,p<.001**	0.009, p=0.025* W=3.4,df=99,p<.001**	0.006, p=0.033* W=2.2,df=37,p=0.036*
RGT2			0.009, p=0.797 W=0.2,df=20,p=0.833	-0.013, p=0.679 W=0.3,df=109,p=0.789		

Box plot angle to the attacked goal (size)



Box plot angle to the attacked goal (size)