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Power Law Distributions in Pattern Dynamics of Attacker-Defender Dyads in the Team Sport of Rugby Union: Phenomena in a Region of Self-Organized Criticality?

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In the region of self-organized criticality (SOC) interdependency between multi-agent system components exists and slight changes in near-neighbor interactions can break the balance of equally poised options leading to transitions in system order. In this region, frequency of events of differing magnitudes exhibits a power law distribution. The aim of this paper was to investigate whether a power law distribution characterized attacker-defender interactions in team sports. For this purpose we observed attacker and defender in a dyadic sub-phase of rugby union near the try line. Videogrammetry was used to capture players' motion over time as player locations were digitized. Power laws were calculated for the rate of change of players' relative position. Data revealed that three emergent patterns from dyadic system interactions (i.e., try; unsuccessful tackle; effective tackle) displayed a power law distribution. Results suggested that pattern forming dynamics dyads in rugby union exhibited SOC. It was concluded that rugby union dyads evolve in SOC regions suggesting that players' decisions and actions are governed by local interactions rules.

Introduction

Modeled as dynamical systems, multi-agent systems like team sports display important characteristics of complexity due to the potential for interactions that emerges between system components (i.e., performers) over time (e.g., an attacker and a defender are two components of a dyadic system in 1 vs. 1 subphases) (Schmidt, O'Brien, & Sysko, 1999; Guerin & Kunkle, 2004; McGarry & Franks, 2007; Passos *et al.*, in press). Previous work has shown how, despite differences in individual constraints (e.g., technical, tactical knowledge, emotional and cognitive skills), both agents in a dyadic sub-system of team sports such as rugby union and basketball explore the space available in front of them to maintain or de-stabilize sub-system symmetry (e.g., Araújo *et al.*, 2004; Passos *et al.*, 2006). For example, previous research found that, in the initial stable state of the sub-system in the team sport of rugby union, the defender started closest to the try line and if an attacker passed the defender with the ball, system organization was destabilized (e.g., Passos *et al.*, in press). After a change in the dyad's structural organization (i.e., the attacker passed the defender and became the closest player to the try line), a try occurred (i.e., when the attacker reached the try area, touching the ball on the ground to score). Also when the connection between the system agents changed (i.e., from non-physical to physical) this outcome was consistent with an effective tackle or a tackle when the attacker passed the defender.

These observations were consistent with Juarrero's (1999) insights suggesting that self-organization under constraints in complex systems is characterized by system agents becoming systematically re-organized in qualitatively novel ways with changes in connection type or structural re-organization occurring between them. Initially it was proposed that each player's behavior was regulated by first order contextual constraints such as the rules of the game, the performance area dimensions and boundary markings, and by each player's role (i.e., the attacker aims to score a try and the defender attempts to successfully tackle the adversary). In accordance with Juarrero's (1999) conceptualization we defined these constraints as a *first order* kind because they initially define the perceptual-motor performance space where action takes place. This type of constraint enhances the probability that specific actions will emerge, such as a defender committing to a tackle at a specific position when defending the score area or an attacker selecting a particular running line trajectory to score a try instead of running randomly across the playing field. Throughout the approach phase in 1 vs. 1 sub-phases of rugby union, there exists a relative independence of both players' decisions and actions. In this phase, one player's actions will not immediately affect the actions of another in a dyad. But as captured by Passos and colleagues in previous research, in order to achieve their personal tactical performance goals, the flow of running line trajectories pulls the players towards the same basin of attraction (i.e., players' trajectories create a region on the field that attracts the dyadic system and where a sudden change in system structural organization could emerge) (Passos, Araújo, Davids, Diniz, Gouveia and Serpa, 2007). It was observed that the players' interactions attracted each other (due to decreasing interpersonal distance) to a critical region of the field where the decisions and actions of each player no longer remained independent. The decrease in interpersonal distance between an attacker and a defender in a dyad was suggested to be inversely correlated with each player's relative dependence and characterized the 1vs1 performance sub-phase of team sports like rugby union. Over time, players' actions in a dyad turned out to be systematically interrelated and each player's intentions did not make sense if separated from each other's decisions and actions (see ideas on complexity of Kauffmann, 1993).

This context dependency led to the emergence of another category of constraints, termed *second order constraints* which exposed the self-organization, emergent tendencies of behavior in complex social systems (Juarrero, 1999). Due to the influence of second order constraints (Juarrero, 1999), attacker-defender behavioral dependence is an emergent property of dyadic systems in team sports, signifying that new behavioral repertoires become available to the dyad as a coevolving system. In spite of the many diverse running lines trajectories available to the players, second order contextual constraints that emerge throughout this stage of dyadic system interactions typically box the sub-system into three possible outcome states: i) *physical contact takes place but the attacker does not pass the defender* and initial system organization is conserved. Nevertheless, the type of connection between the dyad components changes (from non-physical to physical) resulting in the system undergoing a new phase in the self-organizing, emergent process; ii) *physical contact takes place and the attacker passes the defender*. Due to physical contact, the type of connection between the dyad components changes but the main difference between this new emergent state and the previous one is that a change in within-system organization occurs, and the attacker is now the player closest the try line; or iii) *the attacker passes the defender without physical contact* and the connection between the two players remains non-physical. However, the dyad undergoes a phase transition since the players' within-system structural organization changes with the attacker now nearer than the defender to the try line.

Self-Organizing Criticality in Team Sports

In the past decades Per Bak and colleagues developed the sandpile model to describe the existence of self-organizing criticality in nature (Bak *et al.*, 1988). This model highlights that in nature every open system evolves throughout several dynamical states due to catastrophic events. Moreover these abrupt (i.e., catastrophic) changes in system structural organization are due to self-organizing behaviors that evolve to critical states through dynamical processes that occur between system components and are not led by an external agent.

According to Bak's (1996) insights, it could be construed that, in the performance context of team sports, most of the changes in the attacker-defender symmetry can occur through catastrophic events. For example, despite the many small fluctuations that may occur in a pattern of play, the attacker-defender balance can be abruptly broken rather than undergoing smooth gradual transitions. One moment the defender can be counterbalancing the attacker's actions, the next moment the attacker can suddenly break this symmetrical organization, passing the defender and running free to the try line. System evolution to this critical state occurs without the direct design of an outside agent (e.g., the coach). Rather it emerges due to the influence of inherent pattern forming dynamical processes within the system. This conceptualization of system organization is in line with Kauffman's (1993; 1995) modeling of coevolving agent adaptation in complex evolutionary systems. In the coadaptation model of evolutionary processes, when one ecological system component undergoes a change it may be provided with a fitness advantage over other complex system components (e.g., in a predator-prey complex). These components are forced to respond with related changes to enhance their fitness. This cycle perpetuates as the system undergoes continual transitions as each component seeks to gain an evolutionary advantage. Processes of coevolution aim to attain the edge of chaos for a particular system, which according to Kauffman (1995) is a close cousin of self-organized criticality.

These ideas provide a sound theoretical foundation to describe emergent decision making processes (along different timescales) in the dynamics of interpersonal interactions of multi-agent systems in team sports. Processes of coadaptation also exist in multi-agent systems in team sports. These processes set in play a web of compromises where each player progresses towards behavioral goals, but none can be sure about the consequences of his/her own optimal next step due to the constraining influence of other players. As in any biological complex system, at this poised state between order and chaos, agents cannot predict the unfolding consequences of their actions (Kauffman, 1995). This critical state is shaped by the constraint imposed by local dynamical interactions rules among individual system components (i.e., the players). Bak (1996) suggested that in nature the critical states in system order that emerge due catastrophic events are self-organized.

To conceptualize team sports as complex dynamical systems it is important to note that the unpredictable nature of this performance context is due to the intrinsic variability that is available to the players as system agents. During team sport competitions the decisions and actions of each player are constrained by multiple causes that generate multiple effects, and according to Bar-Yam (2004), this is a crucial feature in considering complexity in team games. The potential for interaction between players in a rugby union match, viewed as a complex system, signifies that it is not possible to accurately describe a specific outcome that occurs in a game sustained by a single cause-effect relationship (Passos, Araújo, Davids and Shuttleworth, 2008).

Game Evolution Through Stasis and Quiescence Intermittency

The apparent equilibrium displayed at certain moments of a rugby union match (e.g., a ruck; or a line-out) exemplify periods of stasis that exist between intermittent bursts of activity and volatility in which specific dynamical patterns are formed, such as an attacker-defender balance (e.g., when a defender can counterbalance an attacker's actions). These system patterns can be annihilated as new patterns emerge, such as when the attacker passes the defender in a dyad and runs free until matched by another defender and a new dyadic subsystem is formed. This process in team sports exemplifies the phenomenon of "punctuated equilibrium" which is at the heart of the pattern forming dynamics of complex systems (Bak, 1996). Figure 1 displays data exemplifying the "punctuated equilibrium" that characterizes dyadic interactions in team sports like rugby union. In this instance a clean try is the outcome of attacker-defender interpersonal dynamics in a 1 v 1 dyad.

The phenomenon of punctuated equilibrium in team sports can be characterized as a continuous change in the attacker-defender

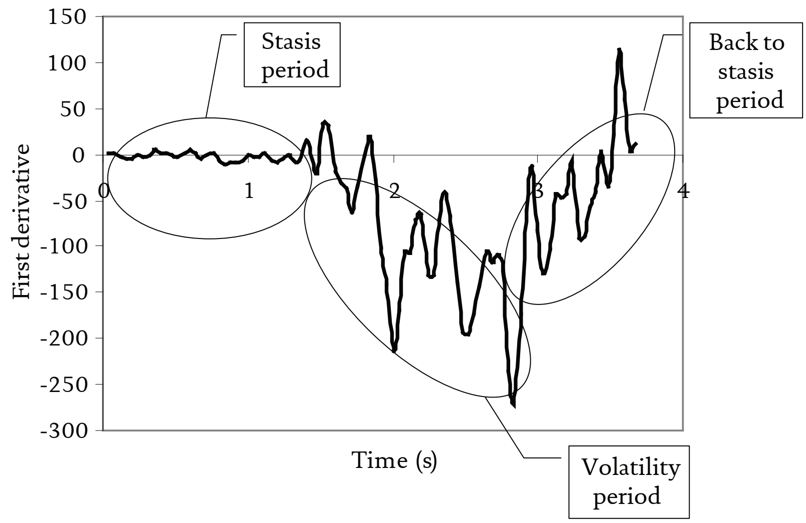


Figure 1 *The Punctuated Equilibrium.*

balance (i.e., at one moment the defender has the advantage, the next it is the attacker who can gain an advantage). This phenomenon manifests itself in changes in critical control parameter values (denoted as 'nested' control parameters by Passos *et al*., 2008), resulting in rich variations of behavior in the dyadic complex system. Near the critical state, interactions between players and nearest neighbors (i.e., team mates and opponents) can become correlated, in a type of domino effect, capturing global system dynamics and leading to a sudden reduction from multiple options to one. In the critical state a slight change in circumstances (e.g., small changes in players' relative velocity) characterizing near neighbor interactions will break the balance of equally poised options leading to an abrupt transition in system order. In other words the coadapting moves of the players shift the local system towards a critical region of the landscape in which it is poised for a transition. Criticality provides the platform for a functional fusion of creativity and constraint in dynamic performance settings. It affords new opportunities for behavior which can fit newly arising circumstances. In this region of criticality it was hypothesized that the frequency of events (i.e., the attacker attempts to pass the defender and the defender counterbalances the attacker's actions) of differing magnitudes exhibits a power law distribution. Such a function is captured when smaller dyadic system fluctuations arise more frequently than larger fluctuations, characterizing system changes such as phase transitions, as agents (players) search for optimal 'fitness' solutions (i.e., breaking or maintaining the equilibrium of the dyad). As each individual in the coadapting dyadic system seeks to enhance his/her success, the whole system inexorably moves (i.e., is attracted) in the cocreated landscape towards a region of self-organizing criticality poised for a transition (Bak & Chialvo, 2001).

To summarize, self-organizing criticality is an underlying principle for complexity and this principle is expressed with power laws (Bak, 1996). In this line of reasoning the aim of this paper is to investigate whether a power law distribution exists for attacker-defender interactions in the team sport of rugby union. If such a distribution in interpersonal interactions were observed, it may be possible to understand when the pattern forming dynamics of a 1 v 1 dyadic system in the team sport of rugby union may enter a region of self-organizing criticality.

Methods

In previous work an experimental task was designed that was representative of a typical sub-phase of rugby union with the minimum number of players involved i.e., the ubiquitous 1 vs. 1 (i.e., attacker vs. defender) situation close the try line. In this research program a methodology was developed, based on videogrammetry, and using two digital video cameras to capture player motion on the performance field. TACTO 7.0 software (Fernandes & Caixinha, 2003) was used to digitized and convert the player images to numbers, and artificial neural networks (ANN) were used to solve the stereo resolution problem (i.e., convert time series data from the two video cameras to three dimensional real world coordinates, x, y, z) (for further details see Passos *et al.*, 2006).

The aim of this study was to identify whether a power law distribution existed for pattern forming dynamics emerging from the attacker-defender dyadic interactions in rugby union (i.e., clean try; unsuccessful tackle; and effective tackle). Bak (1996) proposed that every phenomenon that displays a straight line on a double logarithmic plot may be called a "power law". In this study, the power law relationship referred to log-log plots that were calculated using the 'magnitude of adjustments' on the x axis, and 'frequency (Log of N adjustments)' on the y axis. This power law relationship displayed a specific quantity N (i.e., frequency of changes in attacker-defender relative positioning, called 'frequency (Log of N adjustments') which was expressed as a power of the magnitude of frequency of changes in attacker-defender relative positioning, termed 'magnitude of adjustments', in the following equation:

$$\log N(s) = -\tau \log s$$

To capture the pattern forming dynamics in attacker-defender dyads in rugby union, we identified a collective variable that was suitable for describing dyadic system behavior: that is the angle between a vector from defender to attacker with an imaginary line parallel to the try line (Passos *et al.*, 2008). Data from the collective variable analysis allowed us to identify three different outcomes (i.e., coordination patterns) of dyadic pattern forming dynamics: i) effective tackle; ii) tackle with the attacker passing the defender; and iii), clean try (Passos *et al.*, 2008).

Supported by the collective variable data we calculated the first derivative data for each performance situation which allowed us to characterize the rate of change of relative position between attacker and defender which differentiated the three outcomes of interpersonal interactions of attackers and defenders functioning in dyads (i.e., clean try; unsuccessful tackle; and effective tackle). This procedure allowed us to analyze how rapidly the players adjusted their relative positions over time. If the values remained at 0 ms^{-1}, this result signified that there were no adjustments in the players' relative positions. Conversely, any adjustment in the players' relative positions led to fluctuations in the first derivative values (Passos *et al.*, 2007). An increase in the magnitude of first derivative fluctuations may be interpreted to suggest that the system was entering a self-organized state of criticality, and was poised for a transition (Figure 2).

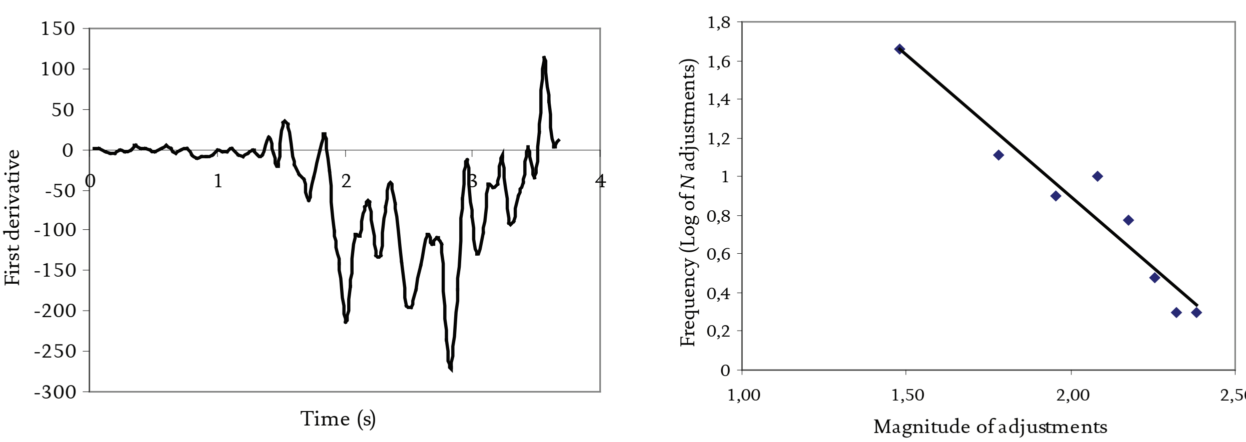


Figure 2 *The rate of change of players relative position and the power law distribution.*

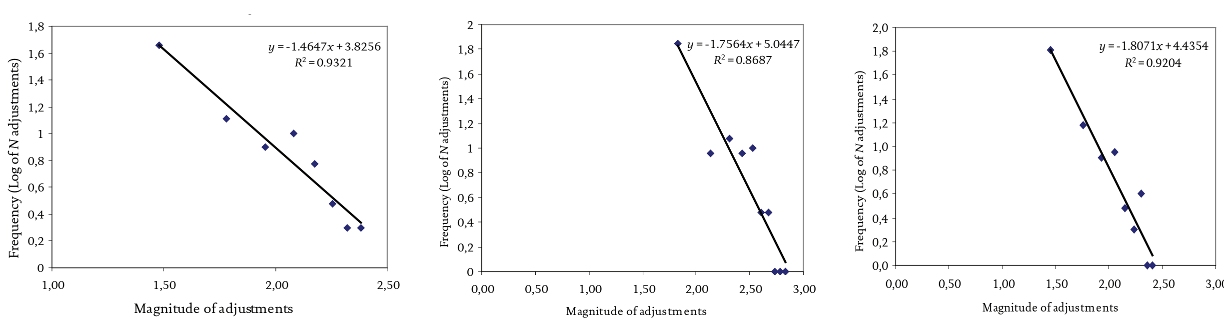
Results

Figure 3 displays three exemplar data curves each representing a coordination pattern displayed in the pattern forming dynamics of the dyadic system: clean try situation, unsuccessful tackle, and effective tackle. Our analysis showed that these three emergent patterns from dyadic system interactions revealed a power law distribution with exponents between 1.4 and 1.8, defined as the slopes of the curve. The magnitude of adjustments for a clean try situation acquired values between 1.5 and 2.4; for an unsuccessful tackle values reached between 1.8 and 2.7; and descriptive curves for effective tackles acquired values between 1.5 and 2.5. The *R* square values for the three coordination patterns revealed a good fit with the model (Figure 3).

Discussion

During each attacker-defender dyadic performance trial it was observed that, adjustments in players' relative positioning with higher magnitudes occurred less frequently than smaller magnitude adjustments. This observation signified that, due to a decrease in interpersonal distance, as well as a number of other task constraints (e.g., players' individual goals), the players' behavior was continuously probing the stability of the dyadic system. This testing of system stability seemed to occur until a specific region of state space where an abrupt and unpredictable change in the dyadic system structural organization occurred. These findings suggested that pattern forming dynamics observed in attacker-defender dyads in the team sport of rugby union exemplified the natural phenomenon of SOC. In this region the distribution of adjustments in players' relative positioning approximated a straight line, exemplifying a power law in accordance with Bak's (1996) underlying principle for system complexity. Supported by local information rules, players spontaneously adjusted their relative positions with information available on each specific performance setting, such as an opponent's relative position and speed. Required adjustments were "scale free" since, due to context uncertainty, there were no typical sizes of variations.

However in geophysical and biological systems evolution from stable states to phase transitions does not involve the need to tune a control parameter. Various studies in our program of work on team sports have shown how the interactions of the individual agents of the complex system seemed to follow their own simple local rules and created unique, poised, global system dynamics in which the motion of one agent might affect any other agent in the system (see also Bak, 1996). In previous work on rugby union, we proposed that the local rules might be assumed to act as potential, nested control parameters (Passos *et al.*, 2007). In that research investigation we identified a specific relation between interpersonal distance and the relative velocity of attacker and defenders in dyads which underwent a phase transition to one of the three possible coordination patterns (i.e., clean try; unsuccessful tackle; and effective tackle). Taken together these findings confirm Bak's (1996) obser-



(a) (b) (c)

Figure 3 *Power law distribution for the three coordination patterns. (a) Clean try, (b) Unsuccessful tackle, and (c) Effective tackle.*

vation that the behavior of complex systems cannot be dependent on the tuning of a single parameter (e.g., temperature in a weather system). Furthermore, in accordance with the sandpile model (Bak *et al*., 1988), the magnitude of an event is unrelated to the parameter that triggers it. In other words large and small events can be triggered by the same kind of cause (Kauffman, 1995). This insight seems to be consistent with the notion of 'multiple causes for multiple effects', a primary feature in considering complexity of team games (Bar-Yam, 2004). Moreover the term "control parameter", which emanated from synergetics (Haken & Wunderlin, 1990), implies that there needs to be an external agent tuning the parameter. The use of this term may not be appropriate here because according to Bak (1996) self-organized critical systems can evolve to a complex critical state without any interference from an external agent. However, building on our previous work, our data suggest the need to maintain usage of the term "nested system parameters", without the qualifying descriptor "control" to identify the important role of local interaction rules as a mechanism that can move a complex system to phase transitions. In our research the nested system parameters that we identified (i.e., interpersonal distance and attacker-defender relative velocity) are emergent system constraints because they became spontaneously coupled without interference from an external agent. At critical values (i.e., corresponding to a bifurcation point, see e.g., Prigogine, 1996), their interaction provoked an abrupt change in structural organization of the dyadic system that led to multiple effects (i.e., the coordination patterns previously presented). These findings correspond to Bak's (1996) notion of criticality and (therefore complexity) emerging "for free"… without any watchmaker tuning the world".

The data imply that in dyadic systems in team sports fluctuations are unavoidable. The large fluctuations observed in 1 vs. 1 attacker defender dyadic systems in rugby union was indicative of coadaptive agent behavior operating in a self-organizing criticality state. In this region minor changes in system parameters (i.e., interpersonal distance and attacker-defender relative velocity) might lead to abrupt changes that characterize the stasis and quiescence intermittency observed in the evolution of competitive team games. Attacker-defender dyads evolve in SOC regions poised at the edge of chaos, where players' decisions and actions are governed by local emergent interactions rules rather than the *a priori* instructions provided by external agents (such as coaches, trainers, parents, significant others). These findings provide some important consequences for training in team sports like rugby union, considered as complex systems. Too much prescriptive advice on decision making and action should be avoided in practice contexts for team sports. Rather, training methods should be built on a 'constraints based approach' with players provided with extensive opportunities to explore the perceptual-motor performance workspace in order to harness emergence and maintain goal directed behavior when entering SOC regions (Araújo *et al*., 2004). Submitting the players to this kind of training philosophy increases their attunement to the relevant information constraints that can lead them to functional decisions and actions.

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