From microscopic to macroscopic sports injuries. Applying the complex dynamic systems approach to sports medicine: a narrative review

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Accepted 30 March 2018
Published Online First 19 April 2018

To cite: Pol R, Hristovski R, Medina D, *et al. Br J Sports Med* 2019;**53**:1214–1220.

ABSTRACT

A better understanding of how sports injuries occur in order to improve their prevention is needed for medical, economic, scientific and sports success reasons. This narrative review aims to explain the mechanisms that underlie the occurrence of sports injuries, and an innovative approach for their prevention on the basis of complex dynamic systems approach. First, we explain the multilevel organisation of living systems and how function of the musculoskeletal system may be impaired. Second, we use both, a constraints approach and a connectivity hypothesis to explain why and how the susceptibility to sports injuries may suddenly increase. Constraints acting at multiple levels and timescales replace the static and linear concept of risk factors, and the connectivity hypothesis brings an understanding of how the accumulation of microinjuries creates a macroscopic non-linear effect, that is, how a common motor action may trigger a severe injury. Finally, a recap of practical examples and challenges for the future illustrates how the complex dynamic systems standpoint, changing the way of thinking about sports injuries, offers innovative ideas for improving sports injury prevention.

INTRODUCTION

Sports injuries can be thought of as the loss of body function or structural integrity that occurs instantly through sports activities.[1] There is a strong correlation between sports injuries and team success,[2] as well as serious financial implications, for example, over $1 billion for Major League Baseball teams in 2014,[3] and £177 million last season for Premier League clubs.[4] The growing number of sports practitioners and the need to provide adequate recommendations for safe practices underpins the great interest in sports injury prevention during the last decade.[5 6]

Existing multifactorial aetiology models reflect the interaction of risk factors in the path to injury.[7–10] These models allow for the possibility that both internal (eg, age, sex and body composition) and external risk factors (eg, rules, equipment and environment) render athletes susceptible to injury. However, as the risk factors themselves are insufficient to cause injury, some inciting event (eg, motor action, playing situation or an opponent's behaviour) is considered necessary to trigger the causal pathway.[8] Meeuwisse *et al*[9] suggested that sports injury risk factors and the susceptibility of an athlete change over time.[9] For example, training load has a dynamic recursive influence on sports injury risk. The same workload may produce a positive training effect (make the athlete perform better and potentially protect against injury by improving conditioning) or under different conditions, increase risk of an injury or, in some cases, cause an injury directly. As risk factors may interact among themselves and change the resulting emergent behaviour, some authors propose the identification of risk factor interactions to detect injury patterns in sport.[10]

Since many risk factors at play (eg, lack of sleep, nutrition status, training surface, musculoskeletal elements such as joint range of motion or tissue recovery state in addition to training load), and the athlete's susceptibility to injuries changes dynamically, we propose, in agreement with some of the experts in the field,[11] to study sports injuries through a complex dynamic systems approach.

Specifically, in this narrative review we offer concrete explanations of non-linear, that is, non-proportional effects that arise as a consequence of interaction between risk factors on different timescales. While linear models can explain sports injuries where the cause is proportional to the effect, for example, a hard blow in the quadriceps produces a severe muscle injury, non-linear models are able to explain proportional and non-proportional cause-effect relationships because they are more general (linearity is just a limit case of non-linearity). Dynamic systems theory (DST) is an area of mathematics that offers useful principles, concepts and tools for understanding and modelling complex, dynamic and non-linear scenarios of the kind that occur in sport.[12]

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DST concepts and principles have been applied to different types of sport-related phenomena (eg, fatigue, decision making or game analysis) and at different biological levels, from molecular to social.[13] Figure 1 shows the shared commonalities and outcomes of two apparently distinct sport-related processes: the path to exhaustion and the path to injury. Embedded in similar dynamic laws[13 14] they can be interpreted as adaptive protective mechanisms that enforce time for recovery. On the basis of the commonalities existing among

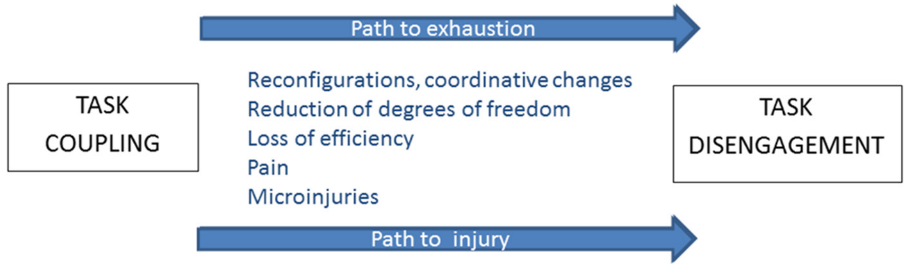

Figure 1 Common features between the path to exhaustion and the path to injury. Both processes bring about task disengagement.

biological processes, some hypotheses and examples extracted from exercise-induced fatigue and, more concretely, from the path to exhaustion investigation, are provided in this text when not available in the injuries' investigation.[15]

Our aim in this review is to broaden the understanding of how mathematical concepts and principles of DST[12] and complex network theory[16] such as *circular causality, synergy, constraint, non-linear effects* and *connectivity* can apply to sports injury prevention. Specifically, we are interested in explaining the why and how of sudden increases in susceptibility to injury via the non-linear behaviour of risk factors and the connectivity hypothesis based on the percolation model.[17] The paper is divided into three parts: (1) The general basis, explaining the living systems organisation and how the musculoskeletal system (MSS) instability arises. (2) The constraints-based approach and the connectivity hypothesis, which are our two main contributions to the topic. (3) Challenges for the future.

MULTILEVEL ORGANISATION IN LIVING SYSTEMS

Motor actions are the product of the interaction between biological components (eg, molecules, cells, organs, limbs) and processes (biochemical or cellular) operating at different timescales (from milliseconds to decades) within a specific context (figure 2). Each level possesses specific properties that emerge through the interaction of individual components on the level below through a process of self-organisation.[18] For instance, muscle cells contribute to form a muscle tendon unit (MTU) but

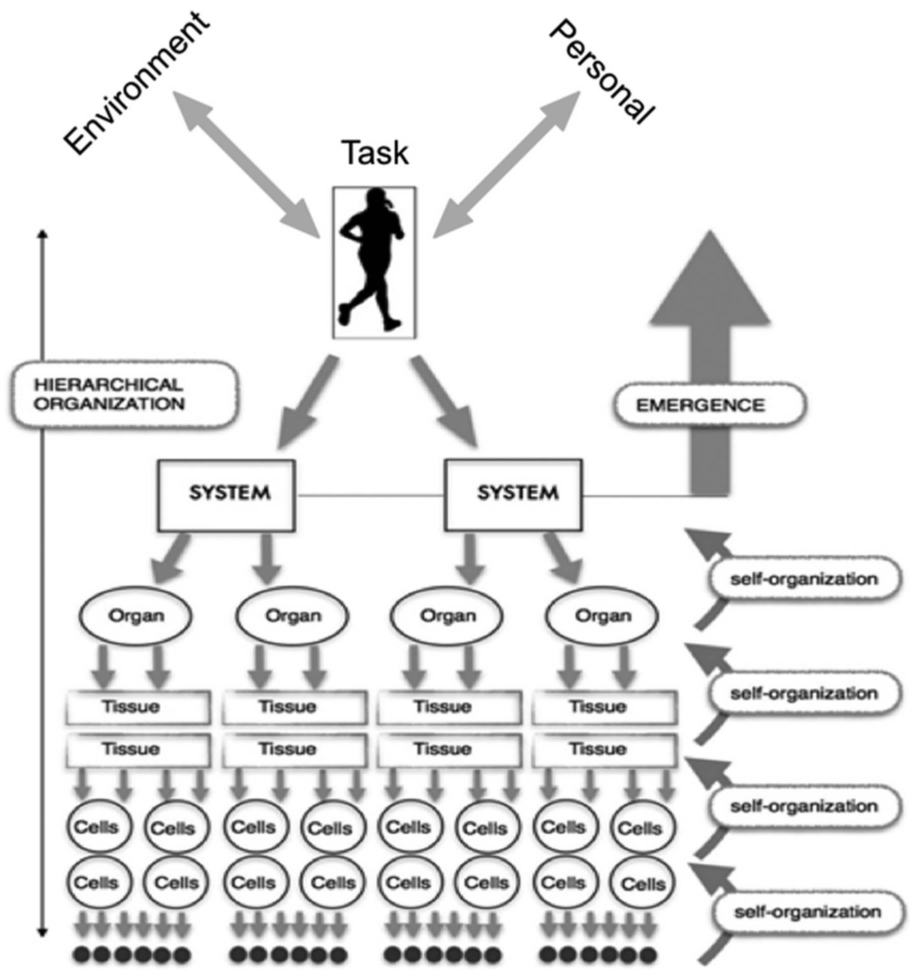

Figure 2 Multilevel organisation in living systems. Processes operating at different timescales (including molecular, organism and social levels) dynamically interact through circular causality and lead to the emergence of new components and properties through self-organisation.

the properties of the latter cannot be explained by properties of single cells.

Although it seems inadequate to establish linear, upward causality relationships among these lower and upper levels, this has been a common practice in the traditional reductionist approaches to sports injuries. For instance, a linear causal relationship would suggest that muscle strains result from excessive tensile forces. This linear relationship has been widely accepted for decades, even though in vivo muscle disruption could not be extrapolated from the sarcomere disruption seen in single fibres.[19] A representative example of this approach is eccentric exercise, which is rated as the most important type of exercise in injury prevention,[20] even if it has a low level of evidence and presents some potential adverse effects.[21–24]

An important DST principle to consider in this multilevel organisation is that the functionality of each level is ensured through *circular causality*.[25] The cooperative behaviour of the components below form the level above and the level above governs the behaviour of the components below. That is, microcomponents (eg, muscle cells) form mesocomponents (eg, motor units) and macrocomponents (eg, MTU) which subsequently govern the behaviour of the components below them. Functionality is attained through a tight cooperative behaviour inside each level and among levels which interact both bottom-up and top-down.

The contextual internal and external changes produced by sports practice require continuous readjustments of these multilevel interactions. For example, it has been shown through the variability profile of coordinative kinematic variables how exercise-induced fatigue changes the cooperative behaviour of neuromuscular components.[26] In the next sections we will examine how continuous multilevel readjustments keep MSS functional during exercise and how the interaction with personal and environmental changes may perturb this functionality.

INSTABILITY OF MSS AND SUSCEPTIBILITY TO SPORTS INJURIES

In(stability)

In DST, *stability* is defined as the resistance to perturbations and rapid return to the system's functional state.[12] When MSS is stable, its microcomponents, mesocomponents and macrocomponents cooperate tightly and flexibly: if one component (or a set of them) is unsettled, the other components make accurate and fast adjustments to restore the functional state. By contrast, MSS *instability* is characterised by rigid and less cooperative behaviour of MSS components that respond with slow and less fine adjustments to perturbations. For instance, overuse and disuse impair MSS functionality and its neural connectivity.[27] Instability implies a delayed return of MSS to a functionally stable state and an infinite increase in its recovery time.

Synergy

To maintain stability in the face of perturbations, MSS self-organises spontaneously through compensatory behaviour occurring at multiple MSS levels. This behaviour is a hallmark of *synergy*. If a set of components reduce or lose their function, other components alter their contributions so that the overall function is maintained.[28] The adaptation to pain sensation through motor coordination changes[29 30] and the increased variability of synergistic components to offset the reduced variability of an injured component[31 32] are examples of MSS compensatory behaviour.

Connectivity

Defined as a spatial measure of connectedness among system components, *connectivity* is proposed here as a coordinative variable to be considered in predicting and preventing injuries. It is hypothesised that: (1) Connectivity is the basis of stability and functionality in healthy MSS tissues. (2) C*onnectivity* is also responsible for linking MSS damaged tissue (microinjuries and mesoinjuries) to produce macroinjuries, as might be the case in dystrophic calcification as a result of recurrent trauma and tendinopathy. With unconnected microinjuries the overall function of the MSS tissue can be maintained through synergetic compensations (MSS stability), but when the *connectivity* within damaged tissue increases, the MSS destabilises. In this unstable state, the addition of a single microinjury may produce a macroinjury.

As available connectivity measures have not yet been applied to the assessment of the MSS state, the variability profile of coordinative variables may be analysed to detect the stable/unstable states of MSS and its susceptibility to injuries.[33] In DST, coordinative variables integrate the organisation of the system's components into a single quantitative value. The type of variability reflects the degree of coupling among the system components and its qualitative reorganisation. Vázquez *et al*[34] have shown that the change in the cooperative behaviour of neuromuscular components as fatigue develops is manifested through the changes in the time variability properties of the kinematic coordinative variable. A small perturbation (eg, pain sensation or imbalance) when the neuromuscular system is unstable, that is, close to exhaustion, can suddenly provoke the task disengagement.

RISK FACTORS VERSUS CONSTRAINTS; PRINCIPLES DEFINING THE MULTILEVEL INTERACTION AMONG VARIABLES

In epidemiology, 'risk factor' is described as any attribute, characteristic or exposure of an individual that increases the likelihood of developing an injury, and it is generally treated as a static variable with proportional, that is, linear, dependencies.[35] By contrast, in DST, the concept of constraints or boundary conditions is used to describe dynamic entities that, interacting non-linearly at different levels and over different timescales, regulate the state (stability/instability) of coordinative variables. Furthermore, short-term changes in constraints are called perturbations. Some conceptual models of sports injuries have emphasised the dynamic interconnectedness and synergistic interactions among different risk factors.[9–11 36] In this respect, the concept of constraint seems more suitable than that of risk factor, especially when considering a DST-based approach to sports injuries.

Newell's constraints model,[37] distinguishing three categories of constraints (organismic or personal, environmental and task-related), has been successfully applied to sports medicine,[38 39] physical therapy and rehabilitation,[40–42] physical conditioning[43 44] and sports biomechanics,[45 46] but only partially to sports injuries.[47] Personal constraints are related to individual characteristics (physiology, morphology, psychology).[48] Although structural personal constraints tend to remain relatively constant over several timescales (eg, anthropometric characteristics, body composition, muscle architecture and typology), functional personal constraints change at a faster rate (eg, muscle strength, mood, motivation, level of fatigue). Environmental constraints also change with time, and are external to the movement system[49] (eg, climate, terrain, turf type, equipment, sports shoes, gravitational forces, implements, referee behaviour and social pressure). Finally, task constraints, related to the task being performed, arise from the interaction between personal and

Table 1 Examples of personal, environmental and task constraints interacting at different levels and timescales. The timescale may vary: for example, anthropometric variables may change faster (eg, timescale of months) during puberty

	Constraints		
Timescale	Personal	Environmental	Task
Fraction of a second	Stretch-shortening cycle	Ball position	Perceived possibilities of action
Seconds	Attention focus	Referee decision	Opponent's actions
Minutes	Acute fatigue	Opponents tactics	Coach instruction
Hours	Goal to win the match, mood	Temperature	Strategy
Days	Motivation	Social pressure	Workload specificity
Weeks	Strength	Rank score	Training intensity
Months	Overtraining syndrome	Seasons, climate	Calendar of competitions
Years	Anthropometry	Fan's support	Sports rules

environmental constraints and can be instructional (eg, rules and instructions) or informational (eg, opponent's actions).[48]

Table 1 summarises some examples of interacting constraints operating at different timescales in relation to the occurrence of sports injuries of personal, environmental and task constraints interacting at different levels and timescales.

The interaction between constraints

Constraints act at different levels and timescales,[31] and arise anatomically and functionally from the interactions between them. Changes in two or three constraints can neutralise each other and have minimal impact on the resulting pattern of coordination due to synergistic compensation. For instance, a reduction in the strength and/or activation of the iliopsoas muscle may result in rectus femoris compensation to generate more hip flexion force.[50] By contrast, a small-scale change in one constraint can have a large-scale non-linear impact on the ensuing pattern of coordination. Consider a small increase of workload that may result in task failure or task disengagement.[26] Due to their interaction with collective variables, constraints are interconnected. Indeed, fatigue, strength and neuromuscular control, considered to be among the main risk factors, are highly correlated; fatigue decreases strength and impairs motor coordination,[51] which, in turn, is tightly coupled to strength.[52]

The non-linear effect of constraints

Human organisms are adaptive and fit their behaviour to emerging constraints. This adaptive behaviour exhibits dynamic non-linear properties (ie, non-proportional changes over time). The relationship between the coordinative variable and the constraints can be continuous and proportional (figure 3, upper panel) or discontinuous and non-proportional (figure 3, lower panel). In the upper panel a small/large change of the constraint brings about a small/large change in the coordinative variable. In contrast, in the lower panel, a large change in the constraint does not lead to any change in the coordinative variable (region A), but a further small change (around the dashed line) produces a large change in the coordinative variable (region B). The behaviour of the coordinative variable in region B cannot be extrapolated from the behaviour in region A, or vice versa, because there is a functional discontinuity between the coordinative variable and the constraint, or a set of constraints. Thus, non-linear effects emerge spontaneously through self-organisation (ie, without being previously designed and/or externally imposed on the system) as a consequence of a small change in the constraint value. Small changes may be compensated for and accumulate without visible effects, before a sudden, further small change produces a qualitative reorganisation. This all-or-nothing, threshold response is typical behaviour of biological systems that cannot be captured by linear or non-linear regression procedures.[12] The activation firing threshold at the muscle cell level, and the qualitative change from asynchronous to synchronous contraction at the motor unit level, are examples of this qualitative reorganisation of MSS components. Although not yet described as a non-linear phenomenon, the literature reports that 60% of hamstring injuries in professional soccer are produced by the 'same' inciting event or action (eg, eccentric action of hamstrings during the late swing or stance phase of the sprint) which has been performed thousands of times without causing a muscle strain.[53]

Effects of workloads at different timescales

Workloads are specific types of constraints playing antagonist effects at different timescales.[54–57] In the short term they produce stress on MSS (inflammation, microinjuries, etc), and negatively affect performance, but in the long term they promote the regeneration of new resilient MSS structures and new motor synergies which increase workload tolerance and performance. Both adaptive responses produce changes in the MSS at different levels (from microscopic to macroscopic) and timescales (from a single exercise bout, to an entire training season). One of the consequences is the changes in MSS stability and its increased sensitivity to recovery periods.[54]

Due to the antagonistic effect of workloads, MSS susceptibility to injuries may change unpredictably, especially over shorter timescales. For example, although repeat sprint training sessions improve endurance in a few weeks,[58] an additional single sprint session of the same characteristics may produce a severe hamstring strain. Interestingly, high training workloads and periods of undertraining and inactivity may increase the risk of injury.[54] In fact, rest also has different time delay effects on each biological level. While de-training effects occur relatively fast at subcellular and muscle fibre levels,[59] longer time intervals are required at cortical and subcortical levels, affecting cognitive functions, such as motivation and attention. Consequently, de-training (or decreased workload) may produce a lack of cooperation among levels, impairing motor coordination and increasing MSS susceptibility. Sports injuries arising after relatively long resting periods, such as those that occur during preseason,[60] may thus be explained by a mismatch between the performance that the athlete tries to achieve and his/her current capabilities. The lack of cooperation among biological levels reduces the synergistic possibilities of maintaining MSS stability[34] and should be carefully considered when designing training programmes. According to the antagonistic effects over different timescales pointed out here, it is likely not the increase or decrease of training workloads per se that affects MSS susceptibility to injuries,[54] but rather appropriate workload provided relative to timings. Consequently, the 'control' of workload timings may regulate the state (stability/instability) of MSS connectivity and thus, its responsiveness to perturbations.

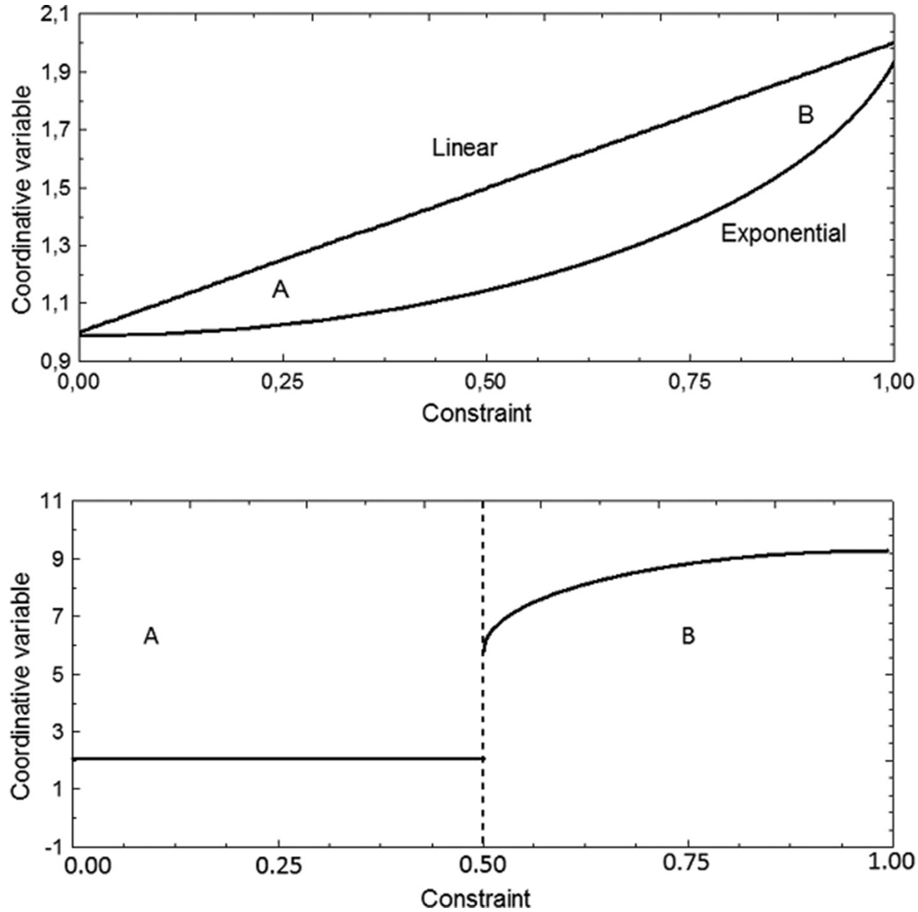

Figure 3 Proportional (upper panel) and non-proportional (lower panel) relationships between coordinative variables and constraints. In the upper panel it is possible to extrapolate the behaviour of coordinative variables in region B from the behaviour in region A, and vice versa. However, in the lower panel the behaviour in region B cannot be extrapolated from the behaviour in region A, or vice versa. The dashed line represents the 'critical' constraint value.

CONNECTIVITY: FROM MICROINJURIES TO MACROINJURIES

According to the connectivity hypothesis, the susceptibility to sports injury is defined as the responsiveness of MSS (representing the macroscopic level) to the addition of a new microinjury (representing the microscopic level), which can be produced by a small mechanical or other type of perturbation. When MSS is stable, the susceptibility is low and a large perturbation, like a large contact or force, is needed to produce a macroscopic injury. However, close to instability, MSS susceptibility to perturbations drastically increases, and the addition of a new microinjury can be sufficient to produce a macroinjury (eg, a rupture or muscle tear). Thus, the connectivity hypothesis unifies the proportional and non-proportional cause-effect relationship of injury formation as a function of MSS susceptibility.

As shown in figure 4, different sets of changing personal and environmental constraints shape the MSS state and the motor coordination during training and competition. In MSS, sites of microinjuries may be conceptualised as nodes of a large network of mechanical couplings with interacting influences. In such large networks, under certain constraints, microinjuries occur and a connected effect (mesoinjuries, macroinjuries) of the damaged tissue may emerge. The connectivity of microinjuries can be seen as an accumulative process occurring at different temporal scales and ending with a non-linear accelerating avalanche that eventually results in a macroinjury. At a short timescale, only microinjuries manifest (except for traumatic injuries) (figure 4A). However, as a small cluster of microinjuries form, the tissue destabilises further and neighbouring cells must be recruited to compensate for its inability to produce force. Thus, an increasing number of motor units become overloaded and more susceptible to injury. As a consequence, at a larger timescale the microinjuries may connect into larger clusters, forming mesoscopic injuries (figure 4B), and at even longer timescales the mesoscopic injuries may suddenly connect and form a giant component or percolation,[17] such as a rupture or muscle tear, or an overt incapacitating macroinjury (figure 4C). This means that under MSS instability an 'event' can be transformed into an 'inciting event'. Such cascading failure effects are commonplace and are also present in power grid or internet breakdowns.[61]

CHALLENGES FOR THE FUTURE; A COMPLEX DYNAMIC APPROACH TO SPORTS INJURIES

Training and competition workloads

As workloads interact with personal and environmental constraints at multiple timescales, they should be prescribed according to general season or mesocycle planning criteria, and according to the fast changing personal and environmental constraints. Research results have detected fluctuations of perceived effort in intervals of seconds during constant workload. These fluctuating dynamics of exercise readiness are explained by coordinative reconfigurations across the effort.[62] A discouraging comment from the coach, a sudden change in the score or an opponent action are examples of fast-changing environmental

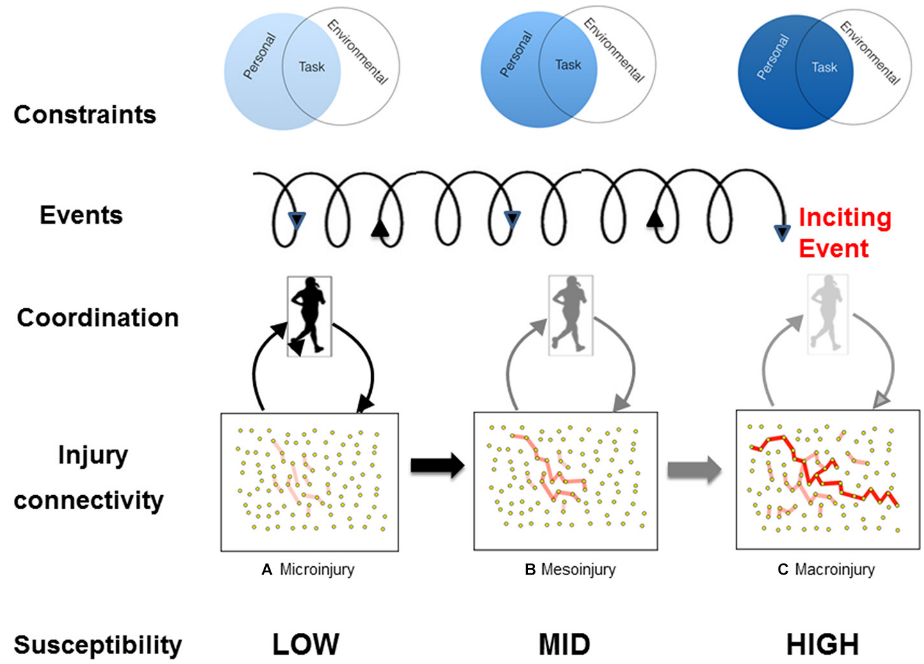

Figure 4 Recurrent dynamics of macroinjury formation based on the connectivity hypothesis. From top to bottom: the interacting personal and environmental constraints form tasks (events) that shape the athlete's motor coordination, which in turn governs musculoskeletal system (MSS) components, their connectivity and susceptibility. The left hand column represents the early stage: the events may form microinjuries (A) but MSS susceptibility is low, as it is in healthy tissue. Middle column (advanced stage): consecutive events without sufficient recovery change the personal constraints further (darker colour) and progressively alter the athlete's coordination (paler colour) accelerating the formation of microinjury clusters or mesoinjuries (B) which enhance MSS susceptibility. Right hand column (final stage): the top-down and bottom-up circular causality between the constraints, the athlete's coordination and injury-connectivity tissue properties may continue to the final inciting event which, due to the high MSS susceptibility, may produce a macroinjury under a standard manoeuvre (C). While in the early stage a large change in the constraints (personal or/and environmental) is needed to produce a macroinjury, in the final stage a small change may be sufficient.

constraints which may alter the internal workload. Injury prevention programmes could be more effective if greater responsibility over workload regulation was given to athletes themselves. The development of this responsibility should start at an early age, and so pedagogical tools should be created for this purpose.

Interoceptive awareness measurements—how do you feel?

Future research should pay special attention to developing body awareness in athletes to recognise early warning signs related to microinjuries (eg, coordinative changes or initial inflammatory responses). The understanding of the injury process explained here and the implementation of adequate subjective assessment tools with pedagogical and exploratory purposes can assist the clinician substantially. This line of research should also be underpinned by the hypothesis that education and self-regulation of emotional and physical states are crucial for the health of the athlete, and career longevity. Until specific subjective assessment tools become available, a simple question addressed to them, such as 'how do you feel?'[63] may provide a rich integrated information regarding MSS susceptibility.

Top-down effects on MSS susceptibility

MSS susceptibility to injuries may change as a result of bottom-up (from subcellular or cellular level to the MSS level) and top-down influences of constraints (from social and psychological levels to the MSS level), recently reported through the association found between coaches' leadership style and injury rates.[64] The effects of fear, anxiety, stress, motivation and emotional arousal on motor coordination,[14 65 66] often disregarded in some models of sports injury, should also be taken into account due to their long-term effects on MSS.

Dimension reduction of constraints

As constraints may drastically change MSS susceptibility to injury, the application of dimension reduction techniques to constraints acting at similar timescales seems suitable for research purposes.[10 11] The projection of coordinative variables in such low-dimensional spaces may pave the way for better detection of the critical regions of constraints that increase MSS susceptibility to injuries.

Variability profile of coordinative variables

There is a need to develop monitoring and recording systems to detect and provide insights into the warning profiles of coordinative variables approaching the tipping point (ie, the emergence of macroinjury) in a variety of sports situations. The variability profile of motor coordination variables has been widely studied in relation to diverse pathologies including overuse injuries.[32 39]

Assessment of MSS susceptibility to injury through connectivity measures

As MSS susceptibility does not correspond to fixed constraint constellations or fixed quantitative values, the development of new objective measures based on *connectivity properties* such as tensegrity[67] is desirable. The precise detection of the clustering characteristics (eg, centrality, mean and maximum cluster size, or preferential attachment measures) of microinjuries and mesoinjuries through developing methods such as 3D

MRI scans are recommended. The assessment of the likelihood of mesoinjuries connectivity and sudden onset of a macroinjury, seem to represent a promising direction for future research. A joint effort of experts in movement science and tissue biomechanics, physicists from the area of statistical mechanics and network theory, as well as bioinformatics and mathematical simulation computer scientists would be needed to create more workable models based on finite element method/percolation theory. In our opinion, a complementary use of inductive inferential statistical and deductive computer simulation approaches can pave the way towards more in-depth understanding and prediction of non-linear mechanisms of sports injuries.

CONCLUSION

Based on DST principles and according to the connectivity hypothesis, macroinjuries emerge as a result of instability spread at the micro, meso and macro MSS levels. We assume that MSS susceptibility to sports injuries is the result of a non-linear effect of constraints interacting dynamically at different levels and timescales. When MSS is susceptible, a small perturbation may connect previous microinjury and mesoinjury clusters, and create a macroscopic effect (macroinjury), such as a muscle tear or tendon rupture. The detection of critical regions of constraints that produce MSS instability and the assessment of microinjury and mesoinjury clustering processes are crucial to prevent the sudden occurrence of macroinjuries. Furthermore, such diagnostic tools for prevention and prediction may help coaches and athletes to control and adapt personal, environmental and task constraints accordingly. The complex dynamic systems approach changes the way we think about sports injuries, and how clinicians, coaches and athletes might aim to investigate and incorporate the constraints perspective into their clinical reasoning and daily practice for both injury prevention and rehabilitation.

What are the findings?

- Personal, task and environmental risk factors (constraints) interact dynamically and non-linearly at different levels and timescales to increase the susceptibility to sports injuries.
- According to the connectivity hypothesis, when the musculoskeletal system (MSS) is susceptible, a small perturbation may connect previous microinjuries and mesoinjuries, creating a macroscopic non-linear effect and accounting for why a standard manoeuvre may trigger a severe injury.
- Workloads should be prescribed according to general season or mesocycle planification criteria, and according to personal and environmental constraints that may change in very short timescales.
- New objective measures based on connectivity properties of MSS and subjective interoceptive capacities of athletes can improve injury prevention strategies.

How might it impact on clinical practice in the future?

- The detection of critical regions of constraints that increase MSS susceptibility, as well as the assessment of microinjury and mesoinjury clustering processes, is crucial to prevent the sudden emergence of a macroinjury.
- As the susceptible state of MSS does not correspond to fixed constraint constellations and fixed quantitative values, it may be assessed through the dynamics of coordinative variables such as the degree of MSS connectivity.
- Emotional and motivational constraints should particularly be taken into consideration due to their long-term effects on MSS susceptibility.
- Through self-monitoring and self-awareness training, athletes can be expected to learn to regulate their workloads and thus, collaborate in reducing the injury risk.

Acknowledgements The authors thank Dr Agne Slapsinskaite and Scott Epsley for their technical work and Dr Karim Khan for his kind editorial help.

Contributors RP, RH and NB contributed to the manuscript's conception and design. DM contributed to the accurate and critical revision of the manuscript as well as approval of the final version. All authors were involved in the preparation and editing of the manuscript.

Funding This study has been supported by the Institut Nacional d'Educació Física de Catalunya (INEFC), Generalitat de Catalunya.

Competing interests None declared.

Patient consent Not required.

Provenance and peer review Not commissioned; externally peer reviewed.

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