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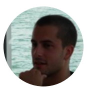
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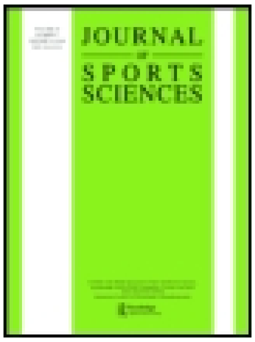

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A scale-based approach to interdisciplinary research and expertise in sports

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ABSTRACT
After more than 20 years since the introduction of ecological and dynamical approaches in sports research, their promising opportunity for interdisciplinary research has not been fulfilled yet. The complexity of the research process and the theoretical and empirical difficulties associated with an integrated ecological-dynamical approach have been the major factors hindering the generalisation of interdisciplinary projects in sports sciences. To facilitate this generalisation, we integrate the major concepts from the ecological and dynamical approaches to study behaviour as a multi-scale process. Our integration gravitates around the distinction between functional (ecological) and execution (organic) scales, and their reciprocal intra- and inter-scale constraints. We propose an (epistemological) scale-based definition of constraints that accounts for the concept of synergies as emergent coordinative structures. To illustrate how we can operationalise the notion of multi-scale synergies we use an interdisciplinary model of locomotor pointing. To conclude, we show the value of this approach for interdisciplinary research in sport sciences, as we discuss two examples of task-specific dimensionality reduction techniques in the context of an ongoing project that aims to unveil the determinants of expertise in basketball free throw shooting. These techniques provide relevant empirical evidence to help bootstrap the challenging modelling efforts required in sport sciences.

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Introduction

Research in basic psychology witnessed a revolution since the late 70's with new concepts and methods coming from ecological and dynamical approaches to perception and action (Bernstein, 1996; Gibson, 1966, 1986; Kugler, Kelso, & Turvey, 1980; Michaels & Carello, 1981; Reed, 1982; Turvey, 1977; Turvey, Shaw, Reed, & Mace, 1981). Those approaches eschew concepts, such as representation, internal models, or mental states, and highlight the relevance of organism–environment reciprocities to explain behaviour. A few years later this new trend also extended its reach to the study of expert performance and skill acquisition in sports (Davids, Handford, & Williams, 1994; Handford, Davids, Bennett, & Button, 1997). As a consequence of their shift towards relational multi-scale processes, ecological and dynamical approaches are in principle better suited for the much needed and demanded interdisciplinary research in sport (e.g., Burwitz, Moore, & Wilkinson, 1994; Davids et al., 1994). Therefore, interdisciplinary research programmes can greatly benefit from an integrated ecological-dynamical framework.

Despite their common grounding, the integration of ecological and dynamical approaches is certainly not straightforward (Beek & van Wieringen, 1994; Michaels & Beek, 1995). The challenge is so complex that some researchers propose to strictly focus on an extended notion of the dynamical approach to further advance a well-founded framework for interdisciplinary research in sports (see Glazier, 2015, for a very recent and well developed example). However, diverse efforts have attempted to define a unitary ecological-dynamical approach from basic research of both disciplines (Beek, Peper, & Stegeman, 1995; Kugler et al., 1980; Richardson, Shockley, Fajen, Riley, & Turvey, 2008; Schöner, 1994; Shaw, Kugler, & Kinsella-Shaw, 1990; Sternad, 2000; Warren, 2006) and from applied sports research (Araújo, Davids, & Hristovski, 2006; Beek, Jacobs, Daffertshofer, & Huys, 2003; Buekers et al., in press; Davids, Araújo, Seifert, & Orth, 2015; Fajen et al., 2008; Montagne, 2005).

In this article, we recapitulate the concepts from the ecological and dynamical approaches to define an integrated theoretical and methodological framework for interdisciplinary research in sports sciences. To anticipate our argument, we consider that a clear-cut distinction between functional and mechanistic explanations of behaviour should be the starting point to develop well-founded interdisciplinary research in sport. Those two levels of analysis concern processes at operationally distinct scales of environmental interaction (i.e., a human can walk towards a goal, while the legs are "simply" moving). However, the aim of this manuscript is to show that functional and mechanistic explanations are not mutually exclusive but complementary scientific approaches to understand behaviour. As discussed below, this perspective also provides the necessary basis for truly interdisciplinary science.

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The theory of "action systems" proposed by Edward S. Reed is particularly suited to account for the functional level (Reed, 1982; see also Turvey, 1977; for an early formulation of the theory), because it integrates in a broad evolutionary and developmental perspective the most relevant notions of the ecological approach (i.e., ecological scale, specifying invariants, affordances, perceptual systems, and smart perceptual devices; Gibson, 1966, 1977, 1986; Runeson, 1977) with the "physiology of action" proposed by Bernstein (1996). The mechanistic level can be accounted for by a wide range of disciplines, as it comprehends any process at sub-personal scales (from physiological systems down to cellular or molecular scales). To organise the exposition of this overwhelming diversity, we take as starting point the problem of redundancy in the motor system as enunciated by Bernstein, who was the first to consider the multiplicity of temporal and spatial scales that shape functional behaviour.

The simultaneous application of functional and mechanistic levels of explanation in real world sports-related situations is an extremely challenging task. In this manuscript we propose a scale-based definition of constraints derived from contemporary research in complex systems to facilitate a scientific approach to the multi-scale dynamics of adaptive behaviour. The dynamical concept of synergy is particularly suited to connect processes at functional and mechanistic levels of description. Due to its intrinsic ability to link disparate elements and levels of analysis, dynamical systems theory is the formalism most commonly used to study self-organisation phenomena (Anderson, 1972; Auyang, 1999; Haken, 1977; Iberall & McCulloch, 1969; Iberall & Soodak, 1987; Kugler & Turvey, 1988; Nicolis & Prigogine, 1977; Pattee, 1982; von Neumann, 1966). To illustrate how this notion of synergies can be used to tackle a research problem from an interdisciplinary perspective we discuss a model of locomotor pointing (de Rugy, Taga, Montagne, Buekers, & Laurent, 2002). Locomotor pointing is the task of placing the foot at a specific location in the space, as seen in the athletic disciplines of long jump or triple jump. To conclude this article, we exemplify the use of this framework in an ongoing project in our laboratory that attempts to unveil the determinants of skilled performance in basketball free throw shooting. We illustrate how to deal with empirical data using a multi-scale and interdisciplinary approach with two sample techniques. Using the information provided by these techniques we aim to develop a dynamical model of basketball free throw shooting similar to the locomotor pointing model. In the next section, we start with the notion of ecological scale and the functional descriptions of behaviour.

Behaviour at the ecological scale: perception and action systems

The old concept of reflex arc constitutes the core notion behind the "physiology of reactions," so often assumed as *the* scientific approach to psychology (Dewey, 1896; Reed, 1982). The reflex arc translates the Newtonian approach to human movement research postulating an inactive organism in static equilibrium with its environment as starting point. This equilibrium is reactively maintained by the animal's reflex responses to the environmental changes that perturb its equilibrium (note the striking resemblance with the three Newtonian principles of movement). As such, this paradigm establishes that psychological activity exists in this passive-reactive loop of stimulations and responses (Dewey, 1896). Contrary to this view, the "physiology of action" suggests that an organism lives in a fundamental disequilibrium with its environment. This disequilibrium creates the conditions for the continuous active engagement with the environment that constitutes the psychological phenomena (Bernstein, 1996; Dewey, 1896). As such, organisms do not react to stimuli that happen to perturb them: Perceptual information is explored rather than received and actions are controlled rather than triggered.

The ecological approach to perception and action is concerned with the inseparable coalition between organism and environment (Shaw & Turvey, 1981; Turvey, 2009). This coalition constitutes what Gibson called the ecological scale, where laws of behaviour are to be found. Gibson (1977, 1986) proposed the concept of affordance to express this constitutive and lawful reciprocity between agents and environments. Affordances are the opportunities for action in the environment, in other words, the goals that intentional actions attempt to actualise. Therefore, affordances are intrinsically meaningful when considered at the ecological scale because they are functional descriptions of the environment from the perspective of an intentional agent. Conversely, actions cannot be understood without the functional descriptions of the environment because they are organised so as to yield specific environmental effects. In Gibsonian terms, actions enable the organism to realise the affordances of the environment. Thus, the problem of action consists in understanding the functions of action systems that enable organisms to behave successfully in their environments.

Agents must perceive both, the possibilities for action (the affordances), and how to control their actions so as to succeed (information-based control, Warren, 1988; 2006; for an alternative formulation see affordance-based control in Fajen, 2007). Functionally relevant relational properties of the organism–environment coalition are specified by higher order information available in the ambient energy arrays. A higher order variable is a complex informational magnitude that can be defined across wide spatio-temporal ranges of the ambient energy arrays. Invariants are higher order information that specifies a property of the organism–environment coalition relevant to control action (note that they can be dynamic quantities, what is invariant is the one-to-one mapping between the energy arrays and the relevant properties). The following example illustrates this process in the context of sports.

A very convenient way to intercept a moving target is to maintain the angle subtended by the current position of the target and the current heading direction (i.e., the bearing angle) constant. The rate of change in bearing angle is illustrative of a high order information, specifying the state of the organism–environment system, and allowing the agent to produce the required velocity adjustments while performing the task. Any change in bearing angle informs the subject about the need to modify the current displacement velocity so as to get the body at the right place at the right time. It has been shown that this high order information is involved in the control of interceptive action performed by humans, allowing functional displacement adjustments to be made (e.g., Chardenon, Montagne, Laurent, & Bootsma, 2005).

A question related to these higher order invariants is how they can be detected. The ecological theory of perception puts forward the concept of smart perceptual devices as a multi-scale model of direct perception (Runeson, 1977). Smart perceptual devices explain how higher order information can be directly detected without postulating intervening mental states or inferences. Smart perceptual devices are soft-assembled dynamical structures that build on the constraints present in a specific task to directly detect (resonate with) the higher order information relevant to control an ongoing goal-directed action or to specify an affordance. The notion of soft-assembled dynamical structures is explained in more detail below in the context of the related concept of task-specific devices.

While perception is specific to the action that the organism intends to control, actions are specific to the functions that they attempt to achieve (and not to the anatomic–physiological mechanisms that participate in their unfolding). Reed proposes an aeronautical analogy to clarify the distinction between functional and mechanistic explanations of actions: "In an airplane, the engines are not components of the flying, though they play a role in flying. Engines are units *in* the plane's flying, but units *of* the plane's flying are aerodynamic factors like lift force and drag. The differences between the components in an airplane and components in flying are due to the fact that an airplane is a thing and flying is a relation" (Reed, 1982, p. 117, italics in the original).

Following Reed's action systems proposal (1982), the components of actions are not muscles, bones, and nerves, but postures and movements. Postures are the functional orientations of the animal with respect to the environment, whereas movements are the changes between postures. Postures can be nested because the different parts of the anatomy can be functionally oriented ones with respect to others, and to the environment. Reed acknowledges the intrinsic variability of actions that Bernstein called "repetition without repetition". However, the variability of movements and postures within actions should be considered with respect to the stability imposed by the task demands because "it is the perceived significance of the environmental situation which controls animal behaviour" (Reed, 1982, p. 112). In the next section, we discuss in more detail Bernstein's account of movement variability with the notions of redundancy and abundance.

Behaviour at the execution scale: redundancy and abundance

Reed's theory of action systems highlights the preponderance of ecological constraints over organic/mechanistic constraints to explain behaviour. The broad evolutionary scope of Reed's theory further reduces the relevance of specific organic constraints on behaviour. We agree with the claim that laws of behaviour are to be found at the ecological scale (i.e., action *is specific* to the intended goals, and perception *is specific* to the performed action), and we are sympathetic with the evolutionary scope of Reed's thought. However, here we are interested in scientific research that can answer the question of how a specific goal-directed action in a certain set of contexts can be performed with dexterity. For that, we have to acknowledge that movements and postures are constrained not only by the task that the subject aims to achieve, but also by the dynamic interactions with the mechanisms used to accomplish it. Let us elaborate the implications of this idea.

The dimensionality of the functional description of a task is typically much lower than the dimensionality of the biological movement system. For example, multiple combinations of joint angles can produce the same position of the hand in the task space. Given this observation, movements are considered "under-constrained" or "under-determined" with respect to the intended task. This redundancy in the action system is known after Bernstein (1996) as the degrees of freedom problem: The number of free parameters in the effectors is much higher than the number of parameters specified by the task. In the perspective to biological movement proposed by Bernstein, the regulation of such a complex system is performed without requiring a central controlling role of any subsystem of the architecture. Rather, the executive role is distributed across all interacting elements that contribute to gradually specify the movement details at their respective spatio-temporal scales.

The distributed control architecture proposed by Bernstein portraits redundancy not as a problem for biological action systems, but as an opportunity to develop new functional adaptations (i.e., motor abundance). In consequence, variability is not the expression of a dysfunctionally noisy biological system, but an essential component of flexible and stable behaviours. Contrary to our engineered control systems, biological systems are typically redundant (the same function can be performed with different elements) and degenerate (an element can perform different functions in different contexts, Davids & Baker, 2007; Edelman & Gally, 2001). Redundancy and degeneracy coupled with controlled variability increase the robustness and flexibility of the motor system. They allow for our ever surprising adaptability to extreme conditions, for example: the ability to compensate for a malfunctioning joint, the ability to perform a principal task under additional contextual constraints, or a higher and less cumbersome ability to resist unexpected mechanical perturbations. It is not difficult to imagine that such a system offers the tools needed to successfully evolve in the extremely demanding settings of high-level games.

Redundancy and degeneracy are essential for flexible and stable functioning of the action system. At the same time they also pose an incredibly complicated problem for the researcher. Why a specific set of actuators from the vast pool of available mechanisms is used to perform a certain action in a certain context? To answer this question we need an account of how the different subsystems involved in the execution of a specific action (most notably, biomechanic, musculotendinous, electrophysiological, and cardiorespiratory processes) are coordinated and reciprocally constraining each other to comply with the functional constraints of behavioural goals to yield specific environmental effects. A bottom-up modelling of all the non-linearities in the subsystems and their interactions may seem as the most straightforward strategy, but it is not a viable option. An alternative approach to the problem is to simultaneously consider the role that constraints play at the different scales and between scales. In the next section we explain in more detail the concept of constraint and present an alternative scale-based formulation that can help us analyse the relationships between functional and mechanistic processes and, thus, facilitate the identification of relevant and feasible research questions in interdisciplinary research projects.

Constraints in the organisation of behaviour

In the previous sections, we have presented the main concepts that are necessary for an ecological approach concerned with the multi-scale mechanisms that participate in the execution of actions. To summarise, we have presented three fundamental notions of behavioural constraints. First, that behaviour is an intrinsically meaningful process at the ecological scale, and it is the task of the researcher to uncover the lawful constraints that support the efficiency of perception and action at this scale. Reciprocally, the second issue is that of the inseparability of perception and action, that contrasts with the clear anatomical separation between afferent and efferent components. This inseparability reveals the need to consider behaviour as the continuous stream of intentional engagement with the environment of an ever incomplete organism. Therefore, perceptions and actions are reciprocally constraining processes operative at the functional scale of the organism adapting to its environment. Third, functional constraints at the ecological scale are not the sole source of natural lawfulness in behaviour. Constraints from processes at other scales must also be considered to provide a more encompassing picture of behaviour. However, the dynamics of the subsystems at the nested scales are so complex and non-linear, that a bottom-up strategy is not a viable one. A simultaneous consideration of the reciprocal constraints between processes at different scales is needed. To tackle this problem, we now turn to a discussion of the concept of constraint in the context of multi-scale complex systems.

In its most general meaning, a constraint can be defined as the scientific denotation of a limitation on the available states of a physical or symbolic system being studied. Every scientific discipline proposes its own set of constraints that helps defining its object of study. The most general and commonly used notion of constraints in the psychological literature is that of the skin-based split between intrinsic and extrinsic constraints (which together with task constraints constitute the model of skill acquisition of Newell, 1986).

The skin-based classification of constraints is inspired by an over mechanistic interpretation of psychological notions. However, there are no principled reasons to accept the skin as the fundamental distinction in the context of perception and action systems. Behaviour at the ecological scale is a relational process that spans components of both the organism and the environment. Thus, the related distinction between incidental and inherent constraints is more appropriated to delimit relevant processes at the ecological scale (Beek & Bingham, 1991; Bingham, 1988). Inherent constraints refer to those constraints that hold for all the ecologically valid contexts in which a task can be presented, like the acceleration of gravity or the inertial properties of the limbs in a reaching task. On the contrary, incidental constraints are those that hold only for specific instances of a certain task, like the relative orientation of a target in a reaching task.

Here we want to propose an additional classification of constraints that complements the inherent/incidental distinction in the study of behaviour as a multi-scale dynamical process. Our notion concentrates on the relative scale of the constraints with respect to the system under consideration, that is, as being either locally or globally limiting the states available to the system.[1] From this perspective, the operationally efficient processes at the ecological scale globally constrain the processes at smaller scales of analysis within the local boundaries posed by those small scale processes, in a reciprocal (circular) interaction between scales. In other words, the functional level of behaviour acts as a global organising principle for the organic processes that interact at smaller scales. The functionally coordinated actions of these organic processes constitute adaptive behaviour. We need to mention here that this notion of constraints builds on the reflections in complex science around the concept of emergence, and how we can scientifically characterise the different philosophical attitudes towards the concept of emergence.

Historically there have been two main opinions about emergence. The weak emergence (Bedau, 1997) considers that there is nothing that really emerges, that is, that the emergent scale is reducible to its components. From this perspective, we use the notion of emergence only as an epistemological accessory to facilitate the description of an otherwise extremely intricate set of fundamentally linear and separable interactions. The strong emergence (Anderson, 1972; Iberall & McCulloch, 1969), considers the emergent process as non-reducible to its constitutive interacting processes. Something really new emerges that is operationally differentiated from its components. It is ontologically emergent because it constitutes a novel domain of interactions. To account for processes in a strongly emergent scale of interaction, we have to develop a new set of concepts and methods that is specifically tailored to them. In this sense, the ecological scale of analysis was developed to account for the organisms' goal-directed behaviour, an emergent process defined by its distinct domain operations.

The scale-based approach is particularly interesting in the debate of emergence because it tackles the definition of constraints from a purely methodological/epistemological point of view (Ryan, 2007) to specify the conditions under which a

[1]Our notion of global and local constraints is not related with the use often made in the ecological literature to denote the degree of generality of an ecological constraint. This use of the term is typical in ecological learning studies, in which the task ecology is experimentally manipulated for each subject to control the processes of education of attention and calibration. Notable examples of this methodology can be found in Jacobs, Ibáñez-Gijón, Díaz, and Travieso (2011), Jacobs, Runeson, and Michaels (2001), and Jacobs, Silva, and Calvo (2009). In the definitions presented here, global constraints would correspond to constraints inherent to the task ecology, and the local constraints would be incidental to the task.

process of emergence is to be considered either strong or weak. An epistemological definition of scale provides an alternative to study emergence in complex systems that avoids the strongly disputed concept of level of organisation. As discussed by Ryan, the epistemological notions of resolution and scope characterise the description used by the researchers in their observations. The scope denotes the spatio-temporal extension of the scientific description being made, whereas the resolution denotes the granularity of the details studied within the considered scope. To investigate the type of emergence that constitutes a process, we first have to carefully choose the description. It should have a scope wide enough to include all the relevant dynamics of the emergent process, and a resolution fine enough to differentiate the component processes.

Once we have carefully selected the description of the system, the observation of local and global constraints hints us about the type of emergence by specifying its ontological scale, that is, the spatial spread of the processes of the systems that does not depend on the process of observation. A global constraint requires the observation of the system as a whole because its limiting effect is defined over the ensemble of states of the system. In other words, the lawfulness in the effects of global constraints cannot be observed if we only consider subsets of the system (Bar-Yam, 2004). In this sense, the existence of a global constraint implies the existence of a strongly emergent process. On the contrary, local constraints can be observed on a limited extension of the whole system, and they imply the existence of a weakly emergent process within the system.

Consider for instance basketball shooting. In this task, there are multiple constraints at the ecological scale that are globally limiting the available states of the subsystems. The intention to put the ball inside the rim is the most obvious one, but other constraints, such as the relative position of the rim with respect to the shooter's release point, or the relative weight of the ball with respect to the action capabilities of the shooter are also notable examples of global constraints at the ecological scale. All these constraints globally limit the possible movements and postures that can be performed to score. Their constraining effect cannot be analytically inferred from the observed states of specific subsets of the player task system. On the other hand, the fatigue of a certain muscle acts locally by limiting the possible states that this muscle can achieve, and a local examination of the muscle properties can provide us a clear picture of the intensity and quality of such constraint. Of course, this local fatigue can have dramatic effects on the overall shooting behaviour or no effect at all due to the interconnectedness between processes across scales, but this is exactly the type of questions that drive the formulation of a scale-based approach to constraints.

The frame of reference that defines whether to consider a process at the local or the global scale is arbitrarily chosen by the researcher to better suit the questions at hand. For example, if we are dealing with the role of the heart in the physiology of the circulatory system, the global level of analysis should be defined at the level of the systemic constraints (such as the hydraulic pressure, the vascular structure, the hormonal state, or the viscosity of the blood), and the local level of analysis could include organic properties of the heart or the arteries, or histological, cellular, and biochemical properties of those organs, depending on the specific research question that we aim to answer. A principled demonstration (in the mathematical sense of our scale-based definition) of the local or global character of each of those constraints is not possible by principle due to empirical limitation, but reasonable approximations can be made with relatively small effort.

In the study of expert performance in sport, the most suitable global level of analysis is that of the task the subject intends to perform (i.e., the ecological or functional scale). Any process that can be ascribed to a more reduced scale should be considered as local with respect to the player task system. We have to define a task in which the subjects performance and improvement will be evaluated, and any resulting conclusion will be specific to this task. However, in doing so we clearly specify the boundaries of the system dynamics that we want to study. It is important to note that the conclusions drawn from the proposed task-specific research cannot be unconditionally generalised to other tasks and environments. Despite the low dimensional functional specification of the task, the complex nature of the non-linear interactions can generate qualitative changes in the dynamics of the system in response to relatively small changes in the performance conditions. This is also the case for generalisations based on inter-individual studies, and the reason to promote individualised studies and analysis in expertise research.

In the next section, we discuss how the concept of synergy as coordinative structure can express the reciprocal interaction between functional and mechanistic constraints. In this notion of synergies, they are conceived as strongly emergent processes at the ecological scale of the player environment system (i.e., at the scale of functional behaviour) that bring about a particular coordination of a plurality of processes at lower scales and are subject to simultaneous scale-based and inherent/incidental constraints. To complete and clarify this highly theoretical discussion, we explain an influential example on locomotor pointing that nicely illustrates how all the different concepts discussed so far have its place in an interdisciplinary research project.

Behaviour as a multi-scale dynamical system

The concept of synergies as coordinative structures relate functional and mechanistic constraints in natural processes of self-organisation in far from equilibrium physical systems (Haken, 1977; Haken, Kelso, & Bunz, 1985; Kelso, Holt, Kugler, & Turvey, 1980; Kugler et al., 1980; Kugler & Turvey, 1987, 1988; Turvey, 1977). This concept was put forward to denote the coordinated action of different elements that serve a functional behaviour. Synergies provide a description of goal-directed behaviour that extends the notion of smart perceptual devices to the domain of action (Bingham, 1988; Saltzman & Kelso, 1987; Turvey, 2007; Turvey, Shaw, & Mace, 1978; Warren, 2006). As such, synergies are concerned with how the organism–environment coalition is temporarily organised into a task-specific device with characteristic low dimensional dynamics. Those task-specific synergies are defined as relational processes that harness both animal and environmental components. The low dimensional behavioural dynamics that characterise task-specific devices are the product of all the complex non-linear subsystems and their non-linear interactions that take part in the assembly of the perception-action loop that defines the task-specific device (Bingham, 1988; Turvey, 2007). The research strategy in this approach is thus to first understand the global dynamics at the behavioural level of analysis, because a direct deduction of the goal-directed dynamics from exhaustive knowledge of the component dynamics is impossible by principle (Bingham, 1988). After a well-defined coherent behaviour has been explained as a task-specific dynamical device, the study of the local dynamics of the subsystems and their interactions can proceed.

This concept of synergy stresses the stability and flexibility of the coordination with respect to task demands. From this perspective, behaving implies the adaptive self-organisation of a highly redundant effector system to comply with a much lower dimensional task. This definition of synergy implies an exquisitely fine-tuned balance between stability and instability at both levels simultaneously, in which the variability of the multidimensional execution system is organised with respect to the functional requirements of the task. This is why the dynamical systems theory is the most appropriate language to study synergies (for a more algebraic and non-dynamical approach to the concept of synergy, see for example Tresch, Cheung, & d'Avella, 2006). The central notion of the dynamical systems theory is the long-term balance between stability/instability. Attractors and repellors are the well-known mathematical objects that operationalise this balance between stability and instability. For a complex system, the layout of attractors and repellors may be so complicated that the notion of metastability is required to account for their dynamical evolution (Kelso et al., 1995).

The balance between stability and instability is a very fruitful conceptualisation in the study of motor behaviour. For a certain behaviour to be functional, it seems obvious that a certain degree of stability in the movements is essential. Reciprocally, the motor abundance notion also points to the functional relevance of movement flexibility. An extremely stable movement system (consider for instance an industrial robot arm) will be able to perform very accurate and repeatable movements, but will have a hard time accommodating perturbations, or adapting the movement to unpredictable time varying constraints. As we all know, these are the kind of situations in which our motor system excels, and not in the accurate repetition of fixed movement patterns. Thus, the flexibility or adaptability of our movements can be expressed as a balance between stability and instability very well tuned to the physical properties of the system and the (often unpredictable) task constraints. Additionally, the ability to quickly reconfigure the movement systems as a whole that goes together with a switch of the performed task is also an expression of this flexible balance between stability and instability.

Despite the sound concepts and solid foundations of the multi-scale dynamical and ecological perspective, developing specific interdisciplinary research programmes is still a major challenge for two main reasons. First, because it demands a careful inspection of the premises that organise research programmes in the disciplines involved to agree in an integrated proposal. Second, because multiple processes and their reciprocal interactions at different scales are considered simultaneously. Experimental evidence and dynamical models from different disciplines must be integrated in a way that allows for the emergence of adaptive behavioural dynamics. In the next paragraphs, we illustrate this perspective through an example that tackles the issue of locomotor pointing (de Rugy et al., 2002). This example is particularly meaningful for our research because it inspired our current project on the determinants of expertise in basketball shooting that will be discussed in the next section.

The model of locomotor pointing from de Rugy and collaborators (2002) provides a very appropriate embodiment of the multi-scale ecological and dynamical approach. The basic premise of their work is to integrate – in a parsimonious way – the functional level of locomotor pointing with the plurality of sub-personal levels of execution involved. Each of these levels of analysis comprises vast amounts of experimental and theoretical knowledge accumulated in the different disciplines concerned with locomotion. Figure 1, presents the simplified logical structure of the model. Due to the richness and complexity of the model, we encourage the interested reader to study the original work and follow up the references there provided.

The functional analysis of locomotor pointing is a perfect example of what is meant by ecological scale, and why the analysis of the task should never be considered as a trivial part of research. We can all intuitively understand what walking means because walking is a natural task for us. However, if we analyse walking as behavioural scientists, we quickly realise that the task is far from trivial. In the analysis proposed by de Rugy et al. (2002), the task of walking is understood as a specific emergent behaviour of the agent–environment system. The to-be-performed task is what binds together all the processes in a coherent goal-directed system, that is, in a task-specific device where both perception and action are organised so as to yield the appropriate behaviours under the prevailing constraints. Therefore, the fundamental task of bipedal locomotion on a plane entails a set of inherent constraints, whereas adapting this task to unpredictable targets entails a set of incidental constraints. These two types of constraints influence all the processes included in the model.

The separation between perception and action at the functional level of analysis is an artificial step imposed by the researcher to facilitate her/his task. In Figure 1, we present this convenient split as two complementary sides of a unique agent–environment continuum. On the action side, we can distinguish gait as bipedal rhythmic locomotion on a hard surface, and pointing as the constrained adjustment of gait to unpredictable target locations. Rhythmic gait can be characterised by its current step period (SP_{curr}), and gait adjustment can be characterised by the required change in step period so as to arrive at a specific point at a specific time (SP_{req}). The adaptive change in step length to comply with incidental constraints of gait is further formalised as d_n and Δ variables in this model. These variables translate the functional specification of gait adjustment into a global modulation of

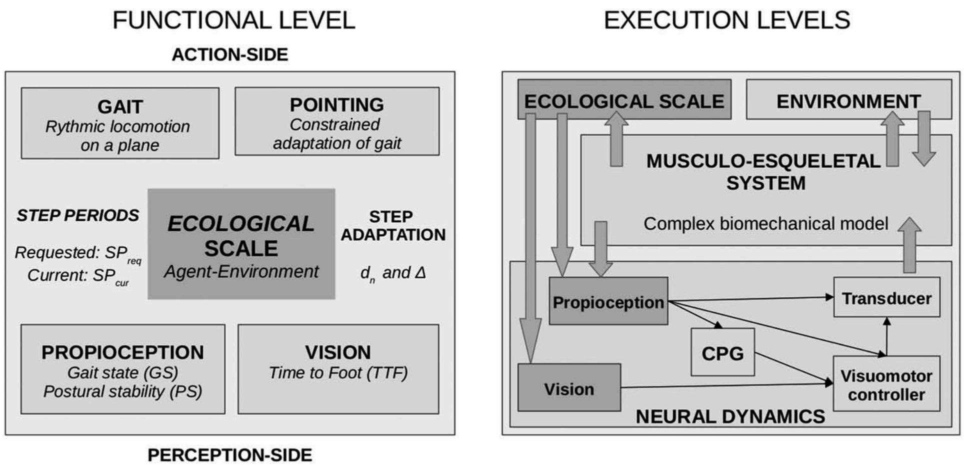

Figure 1. Schematic representation of the logical structure of the model of de Rugy et al. (2002). The left panel presents the relevant processes at the functional/ecological scale that spans the perception–action continuum. The right panel presents the elements and interactions of the organic systems that constitute the execution scale. The entry point of global constraints of the functional scale on the execution scales are depicted in dark grey. Inter-scale interactions are represented as wide arrows, whereas intra-scale interactions as thin arrows. The acronym CPG stands for central pattern generator. See the text for details.

the execution scales so as to yield the prescribed step adjustment.

On the perceptual side the model considers vision and proprioception. Just like action systems, perceptual systems organise as task-specific smart perceptual devices that deal with the dynamic complexity of agent–environment coalitions by exploiting inherent and incidental constraints of the to-be-performed task. Moulded on these constraints, the lawful specification of environmental energy arrays is possible. To reiterate, the information detected by perceptual systems is directly specifying global states of the agent–environment coalition. In this model, proprioception detects the gait state (*GS*) and the postural stability (*PS*), whereas vision detects the time to foot variable (*TTF*). From these variables it is easy to derive the step periods (SP_{curr} and SP_{req}) and the related d_n and Δ parameters. In this sense, all the variables that characterise the current state of the agent–environment system are specified in the ambient energy arrays and directly detected by smart perceptual systems.

The analysis of the execution scale rests on the reciprocal entraintment of the musculoskeletal and the nervous systems. Both systems have inherent oscillatory dynamics due to the lawful constraints laid out by the respective biomechanical and neuronal processes. The reciprocal organisation of their interactions are such that they constraint each other in a way that their outcome is specific to the to-be-performed task (i.e., bipedal locomotion pointing). The mathematical realisation of this complex multi-scale organisation in de Rugy and collaborators' model parsimoniously accounts for the accumulated knowledge on the psychology, neurology, physiology, anatomy, biomechanics, and physics of bipedal locomotion. It is important to note how the global constraints imposed by perceptual systems are related to specific local neural mechanisms in the model (vision and proprioception, in the left part of Figure 1). These neural mechanisms do not assume that perception is simply a local neural process. On the contrary, their specific dynamics cannot be understood as being detached from the global constrains at the ecological scale. The role of these neural systems is to act at the organic scale modulating the dynamics of both the neural and musculoskeletal systems in a way that their overall dynamics maintain the task-specificity of gait at the ecological scale.

It can be argued, though, that the need to postulate specific neuronal mechanisms that transfer the global constraints into the local operational domain of the organic processes is an oversimplification of the most biologically plausible organisation of this multi-scale synergy (a fully distributed regulation). It is not a priori impossible to think of a neuromusculoskeletal enviromental ensemble that is organised in such a way that directly embeds the regulatory role of the global constraints across the all the multiple scales of the system. However, designing such a system is a challenging task. To illustrate this, the mathematical complexity of the relatively simple reciprocal entrainment of the neural and biomechanical oscillators requires years of work from talented mathematicians. In this sense, the development of comprehensive models of real world sports tasks is a challenge of intimidating complexity. Sports skills are complex sets of serial and parallel rhythmic and non-rhythmic actions adapted to sophisticated inherent and incidental multi-scale constraints. Thus, to begin this endeavour we need to accept many simplifications in our models and to develop empirical methods to link scales that can bootstrap multi-scale modelling efforts. As an example, in the next section we present two methods that operationalise the notion of synergy through a multi-scale analysis of variability. These analyses are based on a mathematical definition of the inherent and incidental constraints in the means of execution and how they are mapped and integrated into specific constraints at the functional level.

Empirical methods to link scales

The variability of low dimensional behavioural dynamics represents the fingerprint of the dynamical process of distributed regulation that brings them about. Thus, the multi-scale notion of synergies places controlled variability at the centre of functional behaviour. This consideration of variability in the dynamical approach contrasts sharply with the common practice in sports-related biomechanical and motor control research to postulate the existence of ideal movement patterns that express the optimal motor solution to specific tasks that are considered the criterion to evaluate the performance of all individuals. From this perspective, movement variability is regarded as a consequence of intrinsically stochastic organic processes, and it is therefore a negative factor for performance. As a result, this prescriptive approach towards expertise proclaims the cancellation of variability as the proper route towards ideal motor performance.

The dynamical approach acknowledges the existence of a myriad of individual-specific paths to expert performance. In this sense, our role as researchers is to unveil the different solutions that are available to each practitioner, and look for the optimisation within the boundaries imposed by each participant. The two methods explained below are examples of the kind of the techniques and the type of research that can be used to tackle this problem. However, an exhaustive representation of the techniques available in this extremely active field of research falls out of the scope of this article. The reader should consider this section more as the proof of the concepts that we have discussed in the context of real interdisciplinary research in sport, rather than a catalogue of the whole range of possibilities available for the researchers in sport sciences.

On the one hand, the principal component analysis (PCA) reorganises the multidimensional variability in order to obtain a description of the execution system in a space that ponders the amount of explained variability and the linear independence of the new coordinate system. On the other hand, the uncontrolled manifold (UCM) allows us to directly test hypotheses about the relationship between task and execution stability by analysing the asymmetric distribution of variability in the execution space. Both techniques can establish empirical links between variability of execution with respect to different performance contexts. The main difference between these methods is that the UCM requires a mathematical description of the inherent constraints of the means of execution and their impact on the specific details of the movements and postures performed, whereas in the PCA, those constraints are implicit in the respective distributions of states observed in the high dimensional description of the execution. Thus, the PCA can show the reduction of dimensionality that goes together with a certain task-specific synergy without detailing the constraints responsible for that, whereas the UCM can express those constraints and how they affect the fulfilment of task constraints (Latash, Scholz, & Schöner, 2007).

Principal component analysis (PCA)

The basic idea behind this method is to transform a large number of interrelated variables into a new set of linearly independent dimensions, labelled as principal components (PCs). This term refers to the fact that the PCA redistributes the original variance so that the first component of the new variable space explains the highest percentage possible; the second component explains the highest percentage of the remaining variance, and so on. After this reorganisation of variance, we can attempt to understand the multidimensional execution system using a limited number of components with respect to the amount present in the original data set. These principal components represent global modes of movement coordination. Note that each of these modes is defined by a set of scores that weights the relevance of the originally measured variables in the variability expressed by the PC (see Jolliffe, 2002, for an extended and accessible description).

The PCA can be considered as a mere redescription of a high-dimensional system into a new space in which we can select a highly reduced amount of variables to understand the pattern of overall variability. This feature has two methodological implications. It vastly simplifies the construction of the analysis because there are no hypotheses involved and it amounts to applying a relatively simple algebraic procedure. However, once the analysis is performed, the absence of a hypothesis about the relevance of the execution variability with respect to the task conditions leaves us with the challenge of explaining the meaning of the global coordination modes captured by the PCs. Sometimes this may be rather straightforward, but in general this process has to be accomplished with extreme caution, requiring the simultaneous use of all the sources of information available to understand the PCs and the comparison of PCA between different performance contexts or functionally relevant task regimes (for the interested reader, a more extensive description of this method and its peculiarities in the study of human movement can be found in Daffertshofer, Lamoth, Meijer, & Beek, 2004).

The PCA constitutes a powerful technique to explore massive amounts of multidimensional data in search for patterns that are very difficult to extract from the observation of the original space of measurement. To illustrate, how one could use PCA in the context of sport we present in Figure 2, the results of a sample PCA analysis of the time series of joints angles during basketball free throws.[2] In the plots of the upper corners, we can see that the variance explained by the first PC is 70% of the total variability present in the data set, the second PC explains 20%, and the third PC around 5%. The remaining 38 PCs only account for 5% of the overall variability present in the original data set. Thus, with this linear transformation of the variables we obtain a description of the movement patterns of the free throws that only requires three variables to account for 95% of the observed variability.

The plots in the bottom corners are the projections of the original time series into the first three PCs, and a fourth projection that agglomerates all the remaining PCs. This projection can help us understand the kind of time evolution that each PC captures from the original data set. In this plot, we can see how the first three PCs present the same time evolution regardless of the final result of the shot. In other words, the same 95% of movement variability is present in scored and non-scored shots, whereas in the remaining 5% lies the relevant variability that distinguish good shots from bad shots. An alternative technique to visualise the kinematic meaning of

[2]The preliminary data presented in this article are part of a project that was approved by the local committee of the university. Informed consent was obtained from the participants prior to the experiments.

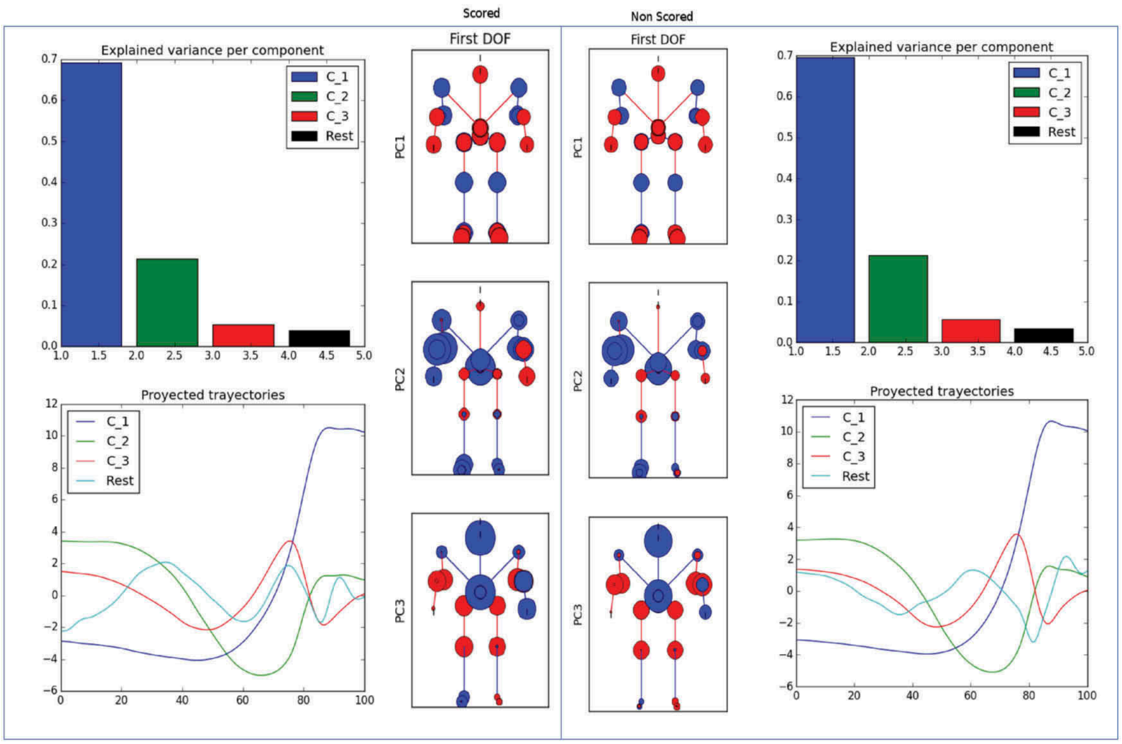

Figure 2. Summarised results of two PCA analyses of basketball free throw time series. A block of 20 trials performed by one participant at the free throw distance and with normal vision was split in two sub-data sets. In the left side of the figure, we present the results for the PCA analysis of the subset of shots that resulted in a score, whereas in the right side of the figure, we present the results for non-scored shots. The bar plots in the upper corners of the figure indicate the amount of variance explained by each PC. The label "Rest" indicates all remaining PCs, from the fourth until the last one (42 in this analysis, corresponding to each biomechanical DOF). The line plots in the lower corners of the figure present the temporal evolution the three first PCs, and the agglomerated effect of the 38 remaining PCs. In the centre of the figure, we present a schematic representation of the scores of each DOF in each of the three first PCs. We only present the first DOF of each joint to simplify the presentation, but it is important to note that joints like the shoulder, the knee, or the hip have up to three DOFs that have also been included in the PCA. The size of the circles is proportional to the absolute value of the score, and the colour indicates a negative sign for red, and a positive sign for blue.

PCs is to reconstruct the original data set (i.e., joints angles) with selected PCs to elucidate the movement pattern that corresponds to each coordination mode. This approach has been successfully used to assess the process of visual information pick up operative in the anticipation of tennis shot direction (Huys et al., 2009).

To complement the previous information we can also consider the weights or scores that input variables have in each PC. In the centre of Figure 2, we present schematic representations of the scores associated with the DOFs of the kinematic chain for the first three PCs. The score is a coefficient between −1 and 1 that multiplies the input variable in the linear combination of input variables that determine each PC. In this sense, a higher score indicates more relevance of the variable in the PC, and the sign indicates an additive or subtractive effect. In Figure 2, we can see that shot types present very similar coefficients for all DOFs in the first three PCs, thus reinforcing the idea that they represent a common global movement pattern.

Uncontrolled manifold (UCM)

The UCM is a method to analyse movement variability based on the assumption that biological motor control exploits the abundance of solutions in redundant effectors. Inspired by the Bernstein perspective to motor control, the UCM analyses movement performance using the concept of stability of the dynamical systems theory. The UCM methodology considers that the low dimensional task-relevant variables must remain stable along a movement, thus recognising the primacy of task-level descriptions to understand behaviour (for some interesting experimental applications of this method see Scholtz and Schöner, 1999; and Schöner and Scholtz, 2007).

Contrary to the PCA, the UCM requires the proposition of an a priori model that describes the constraints in the high dimensional space of execution, and a model that relates changes in the execution space with changes in the task space. For instance, if the description of the execution system is based on a model of the joints as mechanical links between rigid bodies, we need to produce a mathematical description of the kinematic chain, and an expression for a certain task variable (e.g., the vector of relative position of the hand end point with respect to a target in space) in terms of the kinematic chain (a mapping between execution and task variability). Figure 3 presents an example of a kinematic model used to describe basketball shooting. The figure also illustrates the kind of body-task variability mapping that the UCM helps us understand. Take for example, the hypothesis that the position of the left hand endpoint in the global coordinate system of the court is a behavioural variable that the motor system should try to control because of its crucial relevance for the accomplishment of a successful basketball shot. Rooted in the dynamical notion of balance between stability and instability,

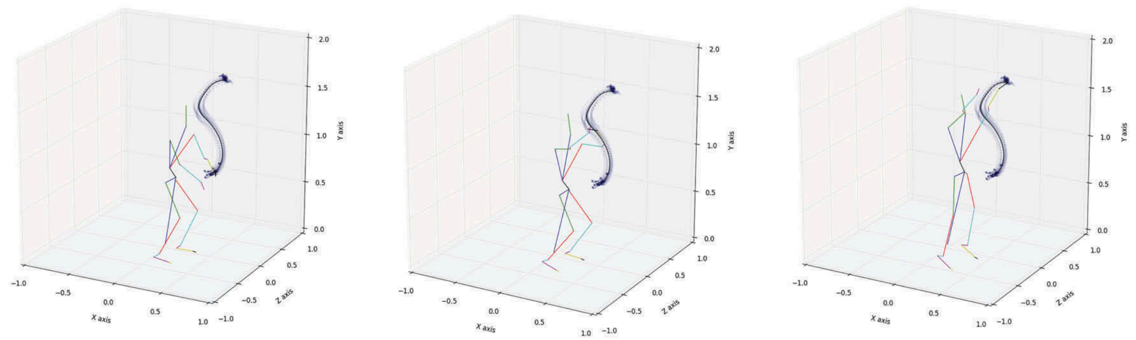

Figure 3. Schematic representation of the average time evolution of free throws. The figure presents a geometrical model of the kinematic chain used to analyse the data during three moments of the shot, together with the average trajectory of the left hand endpoint, and the dispersion cloud from the ensemble of 20 trials for the same body (left hand endpoint). With this plot we can better understand the meaning of controlled and uncontrolled subspaces of the movement execution system. See text for details.

the UCM assumes that the different degrees of control can be observed in the empirical data as different degrees of variability. As detailed below, the UCM analysis splits the variability at the execution level with respect to the variability at the task level.

Regardless of the method used to obtain the mapping between execution and task spaces, the redundant degrees of freedom of the effectors are partitioned in two subspaces with respect to their effects on the task variables. Those combinations of degrees of freedom that do not affect the task variable form the UCM (in the example of Figure 3, the sets of joint angles that keep the global position of the left hand equal to the average), which is supposed to be uncontrolled (or less controlled) and thus less stable (more variable) than the degrees of freedom that affect the task variable (that is, combinations of joint angles that deviate the left hand position from the average). The task relevant combinations of degrees of freedom form the controlled manifold (CM), and are assumed to be more controlled and more stable. Recapturing the dynamical perspective, the UCM method is based on the assumption that the effectors are organised in such a way that makes them more stable to perturbations in the task-relevant manifold. This control strategy does not impose a specific optimal solution to the execution parameters but a manifold of equivalent trajectories that can lead to successful completion of the task. Even more, in the framework proposed by the UCM, it does not make sense to talk about optimal trajectories any more.

Interdisciplinary research across scales

Using the techniques explained in the previous section and the theoretical framework presented here is a straightforward method to perform interdisciplinary research. There are two levels of interdisciplinary approach involved here. First, an interdisciplinary approach intrinsic to the methods themselves, because they are designed to unveil the cross-scale constraints that link dynamics of execution level processes (such as joint kinematics, biomechanics, or electrophysiology, depending on the magnitudes measured) with the ecological dynamics of the performed task. On a second level, an interdisciplinary approach extrinsic to the methods can be obtained by performing repeated analysis under different regimes of performance and comparing the changes in the multi-scale organisation of the behaviour. In our basketball shooting research, we are currently analysing the effect of physiological fatigue and social stress on the performance of expert players with this type of interdisciplinary method. In the examples presented, we compare the different multi-scale organisations of behaviour in scored and non-scored shots in neutral conditions of performance (without additional manipulations) to understand if there are principled processes that underlie successful shooting.

Conclusion

The ecological approach depicts organisms as actively engaged with their environment in a specific and reciprocal relationship. This active engagement with the environment translates perfectly with the notion of the expert player seeking to deploy his actions on the court. The player is not just reacting to the environment but actively shapes the opportunities for action and generates optimal circumstances to achieve the intended goals. The ecological approach attempts an explanation of behaviour as a relational process that is globally constrained by low dimensional magnitudes that are directly relevant to the organism as a unit of action in its environment. In our portrait of the ecological-dynamical approach, organic mechanisms are not disregarded but they are considered complementary to understand the unfolding of skilful behaviour. To better understand the nature of this complementation between functional behaviour and organic mechanisms, we have presented an extended notion of constraints that also considers the multi-scale nature of behaviour. We have identified the ecological scale with the global level of analysis, whereas the great diversity of local levels of analysis has been denoted as execution scale. Finally, we argued that the notion of synergies as coordinative structures fits nicely as the central concept of a multi-scale approach to behaviour. To illustrate the explanatory power of multi-scale coordinative structures, we discussed a model of locomotor pointing that represents our approach.

In the ecological-dynamical perspective variability is a fundamental property of biological movement that expresses its ability to exploit the redundancy and degeneracy of the motor system by tuning the balance between stability and instability. Therefore, sport expertise should be rather conceived as the appropriate control of the variability in order to adapt movements to the complex and often unexpected task-specific constraints that sport skills pose to the individuals. As a consequence, instead of looking for the optimal and ideal motor performance in a task, we should study the unique solutions that each individual can extract from the set of constraints that define her/his specific coupling with the environment.

We have discussed two examples that use real data from a basketball free throw shooting task to demonstrate how to bootstrap the very challenging multi-scale modelling efforts required for interdisciplinary research. The examples were not provided as a complete overview of the analytical possibilities, but as a proof of the applicability of the concepts and perspectives proposed. The gist of these methodologies is the connection between execution and functional constraints using mathematical techniques to link high-dimensional spaces of execution with low-dimensional descriptions of the task at the ecological scale. This is a very active field that concerns all scientific disciplines, and an exhaustive review of the most relevant methods is out of scope of this article and would indeed require a rather large monographic study. However, we hope that the two examples provided here can help the reader to better understand the significance of the approach for the development of interdisciplinary research projects.

A ready-made path towards interdisciplinary research is certainly not possible. The diversity of interesting research questions, methods, and disciplines that can converge (especially in the context of sports sciences) is overwhelming, and a systematic recipe towards interdisciplinary research may have more negative consequences than the solutions it can bring. In this article, we have taken a long and certainly not always simple theoretical detour because it is our belief that rather than seeking for recipes and simple solutions, what is needed to spur interdisciplinary research is a wide perspective to interpret the questions that may be posed, and the feasibility to answer them within a scientific framework. To that end, we have presented basic theoretical concepts close to their philosophical rooting. After several centuries of indisputable success of analytical and reductionist approaches to understand simple physical systems, it seems now obvious that the solution to complex biological, psychological, and sociological problems requires an encompassing, integrative, and holistic attitude towards research, as we have tried to show in this manuscript.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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