25 Sport Sciences: An Ideal Field of Play for Integrated Knowledges

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We are not students of some subject matter, but students of problems. And problems may cut right across the borders of any subject matter or discipline.

Karl Popper

Summary

Sport is an extraordinary challenge for human physical and scientific knowledge. It lies in the complexity and unicity of open living systems, exceptional and unrepeatable performances, uniqueness of each body and individual characteristics, and redundancy of degrees of freedom (DOFs). Further challenges arise from small numbers of top-level athletes and competitions, the difficulty of carrying controlled experiments, non-falsifiable results, experimentally impenetrable areas, search for valid surrogate endpoints, not direct measurability of some human characteristics and consequent conceptualization of multifactorial constructs, variability and unpredictability of environments, selection and verification of useful models, and heterogeneous, spread, and tacit knowledge. Sport is a multidimensional and complex intersection of Physics, Chemistry, and Biology. Science of complexity and networks, integrated Biology, Big Data, models, and modern techniques brought several answers to old questions and opened new challenging frontiers to improve sport sciences. An integrated approach is proving increasingly valuable and necessary.

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1 Introduction

Sport represents an extraordinary field of play to challenge human limits as in physical performance as in scientific knowledge. Challenges for modern sport are the complexity of open living systems, exceptional and unrepeatable performances, uniqueness of each body and individual characteristics, redundancy of degrees of freedom in skeletal movement, difficulty in carrying controlled experiments, non-falsifiable results, small numbers of top-level athletes and competitions, presence of experimentally impenetrable areas, search for valid surrogate endpoints, not direct measurability of some human characteristics and consequent conceptualization of multifactorial constructs, presence of variable and unpredictable environments, the selection and verification of useful models, and heterogeneous, spread, and tacit knowledge [1]. When athletes differing in age, anthropometric and functional characteristics, technique, training, and sports equipment obtain almost the same result to hundredths of a second or millimeters, when long races end at photo finish and gaining or losing the podium is a matter of details, what knowledge can find the *causes* of success or defeat? For a long time, there have been various approaches adopted to explain and improve sports performance, and from here comes the first issue. Are we dealing with a *single sports science* or with *multiple sport sciences*? A core of the matter hides under an apparently innocuous linguistic detail. The use of singular or plural has deeply to do with the conception itself of the unity of science and the scientific method [2] and has crucial practical implications. The Anglo-American, Popperian view of science entails a clear hierarchy between the *hard* science, which is experimental, verifiable or falsifiable, and the *soft* sciences regarding humanities, being theoretical, interpretive, historical, and where experiments are not always under control or repeatable. So, science and his method are only one, singular. However, sport is a multidimensional construct at the intersection of Physics, Chemistry, and Biology, where some areas are experimentally impenetrable, chance plays its role, and the presence of circular causality dismantles simple explanations made of cause–effect chains. Although the concept had already been grasped for centuries, studies on complex systems have finally established that in systems with numerous internal links and degrees of freedom (DOFs) or featured by nonlinear dynamics, it is not always possible to use the Newtonian–Cartesian approach. More clearly, the whole is not always the simple sum of parts, somewhere new information is generated and stored, links, patterns and connections are crucial, and some features present at certain levels are not visible elsewhere. Information is not reducible beyond a certain threshold, so the memory acquired by complex living systems at the highest levels is not detectable in their sub-components. It is not only a matter of ignorance but also of principle: no single level can explain all the others [3, 4]. From Poincarè to Einstein and Schrödinger, from Russel to Popper, from Gödel to Turing, Lorentz and Mandelbrot, an extraordinary heritage of the XX century Science is that human knowledge has impassable limits. No general solution exists to Newton's motion laws for more than two bodies; it is not possible to entirely separate an observed phenomenon by his observer. Even formal axiomatic theories have boundaries of provability. Unlike solar eclipses, the weather becomes unpredictable only after a few days, clouds are better conceptualized as fractals than spheres. Organisms and mechanisms are completely different things, even if sometimes we tend to confuse them. A cell is not the simple sum of atoms; an organ is not the sum of cells; a living being is not the sum of organs. The same unit has completely different properties in vivo, in vitro, or in silico. So, any sport outcome is not just a combination of a knee's range of motion, the oxygen uptake, a lactate threshold, or ski wax. The analytic approach is reductionist and mechanistic and works when building a skyscraper, a mobile phone, or sending the man to the moon. In sport and other disciplines, a powerful working strategy is analytic and reductionist, dividing the system Athlete-Equipment-Environment into single parts to study and improve each one singularly. Taxonomies are normally used in various fields to quantify human tasks and performance [5–11]. Single improvements are supposed to be transferable at different levels and additive. It is natural in our way of facing reality and reasoning linearly, and it works. From here comes the powerful concept of so-called *marginal gains*, a transversal strategy is to improve performance from the extraordinary results of Team GB Cycling during the London 2012 Olympic Games. It does not matter how much every variable impacts the result, our understanding of how this happens, and if they are not homogeneous. Indeed—precisely because we do not know *why*, *how,* and *when*—we strive to optimize all of them together. No matter if it is an aerodynamic detail or a comfortable pillow, because the aggregation of several small gains, none of which singularly dominant, can result in the improvement of overall performance [12]. Cycling, sailing, skiing, bobsleigh and luge, rowing, or tennis are sports heavily influenced by technology and, consequently, by the continuous search for every possible small gain. However, even an unchanging sport as swimming, dominated by physical constraints such as the water density and where—have been banned the technological swimsuits—the athlete relies only on his muscles and technique, benefits are coming from many small details in talent selection, training and technical techniques, and nutrition. The process is visible in the slow but continuous improvement during the years of performances in all swimming styles and distances. A powerful strategy is to perform simulations and sensitivity analysis to assess single variables' importance [13–15]. This is the first practical demonstration of the need for many different pieces of knowledge that must be integrated to work, especially in top-level sports. It is like a sort of puzzle where the pieces are placed on different levels, and it is not easy to get the whole picture. However, even if commonly used, the term *integration* has different interpretations in different contexts and is not always properly defined. Sports science usually alludes to multiple approaches: single features are seen and studied from different perspectives and disciplines [16]. Afterward, the parts are put together to produce a global result where only a single variable depending on the chosen metric, such as a time or a distance, is taken to build a ranking and become a champion. The system is open, complex, and the connection between parts and outcome can be speculated within only certain assumptions. A working strategy is to set intermediate and heterogeneous surrogate endpoints: functional qualities, biomarkers, oxygen consumption, skills, forces, power, speed, elasticity, asymmetries, electromyographic profiles, fatigue, and equilibrium are examples of variables thought to be meaningful markers to predict performance. However, the relationships between balance [17], strength [18], or technique [19], and the elite performance are far to be clear and need to be adequately validated [20–23]. A challenging example is the classification process in Paralympic sports: to guarantee fair competitions, athletes are clustered according to their residual functionality, and minimum impairment criteria are established to assign each individual to classes of a single discipline [24]. Remaining within the visible and measurable, although the human body is physically continuous, disability and motor functions are not. An amputation a few centimeters just above or slightly below a joint radically changes its functionality and, consequently, the athlete's performance obtainable. Ethics aside, the scientific controversy surrounding Oscar Pistorius represents the ideal example of the challenges posed by the need to integrate knowledge in complex and multi-hierarchical systems such as the athlete-sports equipment. Pistorius and few other bi-amputee athletes with their sophisticated double carbon fiber artificial legs are a complex and never seen before interaction between Biology, Physiology, Mechanics, and Technology. Are the missing muscles disadvantageous because there is less available propulsion, or rather advantageous because the system's inertia decreases, the athlete produces less lactate, and has springs instead of joints? How to deal with the technology, material, and geometry of prostheses? How do these characteristics apply to different types of track and field competitions? How much time do they earn? Is it reasonable for these athletes to compete with the able-bodied? It has been claimed that it is a kind of new technological doping [25, 26]. It is impossible to conduct controlled experiments or verify/ falsify some statements concerning the fairness of leaving them to compete against other mono-amputated or non-disabled athletes. Over the years, the scientific and technical controversy has been hot. Numerous discussions were opened about the anatomy, physiology, and running biomechanics of animals and humans, laboratory and field studies have been done worldwide. Many scientific papers published, statements, and rebuttals animated the debate. However, due to the problem's particularity and complexity, a final consensus has not been achieved [27]. The feasibility and replicability of controlled experiments, as required by hard science, is another key point. Unique outcomes with the impossibility of replicate a controlled test is a great challenge for any researcher [28]. It is impossible to re-run a race or send backward the time to change a training program after it has been done. Due to its historical nature, complexity, chaotic nature, limitations in time and resources, practical and ethical issues, it is not always possible to find and test all causal chains and, sometimes, understand why an athlete wins or loses [29]. The impossibility of replication sets insuperable limits on the generalizability of any law because there is no single way to conduct an experiment, finding answers, and falsifying hypotheses. Time and resources are limited; every athlete is different, has a unique personal story, and interacts with a continuously variable environment. Tiny differences between top performances, number, and level of competitors, external factors such as injuries, and the finite number of events in a season can shuffle the cards entailing that the strongest athlete or team will not necessarily emerge [20, 30, 31]. Some questions will remain unanswered and paths unexplored. Doping is a scourge of modern sport; cheating threatens fair competition's very roots and meaning. Therefore, anti-doping is a major challenge and implies the integration of different pieces of knowledge. For ethical and legal reasons, protocols and methods used for other drug investigations cannot research the doping effects on performance: a healthy person should not be used as a guinea pig receiving a potentially harmful drug just to do experiments. However, the lack of scientific methods, poorly controlled evidence about how a single drug translates to performance, the choice of adequate surrogate endpoints to evaluate, understanding if and how it works are all problems difficult to overcome [32]. In complex systems, the whole is not just the simple sum of the parts; rather, the study of causation requires its own conceptualization [33]. So, the integration of knowledge is a challenging and promising strategy for future research in sports.

2 Movement in Sports: A Starting Point

Any sport challenges different human abilities and skills, requiring the execution and control of some movements. Even in static disciplines such as Shooting or Archery, every gesture must be performed alternately, creating and breaking a position and a new balance. So, the study of human movement is transversal for all sports. The living bodies are flexible to perform a wide variety of movements. A crucial property of biological tissues is *viscoelasticity*—the ability to feature at the same time viscous and elastic comportment—on which depend stiffness, loads, movements, and, ultimately, the technique [34–36]. It has redundant functional DOFs in muscles, joints, movements, and at the neurophysiological level. Internal dynamics, viscoelastic and soft tissues, wobbling masses, and not uniform density distribution are additional features. Males, females, and different athletes have unique body shapes, size and anthropometric characteristics, muscle, mass, and fat distribution. Care is required when bodily characteristics are generalized between athletes. Usually, highly customized studies and optimizations are needed. Muscles span over multiple joints and never act in isolation, showing length-dependent properties. Impulses and resulting movements are circles of interaction between the nervous system and sensory environment, so no simple correspondence between a motor task and a motor solution exists. Even when performing the same movement repeatedly, the kinematics is not identical [37]. Due to the nonlinear combination of gravitational and apparent accelerations with the kinetic chains' geometry, great analytical difficulties arise in studying fast and multi-joint movements. The relationship between the innervational impulses and consequently evoked movements is extremely complex and not univocal [13, 37]. When studying the kinematics and dynamics of the limbs in the gravitational field, the mechanically complex interaction between different muscles and the non-constancy of the moment of inertia comes up. So, the equations for movement become complex. As already understood by Bernstein in the early twentieth century, *cannot exist an unequivocal relationship between impulses and movements; movements are possible only under conditions of the most accurate and uninterrupted agreement—unforeseen in advance—between the central impulses and the events occurring at the periphery, and are frequently quantitatively less dependent on these central impulses than on the external force field* [37]. Reduction of DOFs, dimensional compression, and compensations are operated by the coordinative structure [38], but even the same final motor solution may be highly individual. An extraordinary principle of Biology and cybernetics is *equifinality* [39]. It states that for open and adaptive systems, there might be the same state derived from different boundary conditions and different paths. So, the unique motor strategies and variability of single athletes may result in very similar outcomes. The systems show a strong path-dependence making it improbable that only a single and generalizable *best way* exists [40]. Human bodies are noisy and not fully determined systems, both these features being crucial in movement analysis and comprehension. The long practice performed by athletes before competing in sports requiring the execution of accurate motor skills such as tennis and golf is not only a warm-up but rather likely a necessary recalibration of a very noisy and high learning-rate sensorimotor network [41]. From the classic deterministic point of view, the movement variability is considered as noise or error. It comes from adaptations in the musculoskeletal system, changes in the external environment, and bio-variance precluding the accurate replication of technical movements and affecting tests [42]. Instead, the modern and integrated view supposes that the variability may contain important information about nonlinear properties of the system [43, 44], the potential risk of injury [45], some underlying learning and training process, latent pathologies and incomplete recoveries, or environmental changes [46]. Singles' kinetic and kinematic parameters describing the technique behave differently than the whole system, so the association of variability with skilled performance is unclear and intriguing [47]. It is worth considering that the top athletes usually feature performances with lesser variability, and males are more regular than females [48–51]. Not all human features are formulable as simple variables. What is a *sports technique*? How to define, analyze, and teach it [52]? Is it unique or different solutions equally effective are possible [53]? Scientists and practitioners analyze athletes' movements in different ways: the former selecting specific, measurable variables, the latter observing the movements of the whole body. This reflects the ancient debate of medicine between organism and body, whether the disease should be seen regarding single organs or living beings as a whole. The selected point of view consequently affects approaches, strategies, and tools to be chosen. More, after years of practice, even skilled athletes fail to reproduce the same movement [43], and this explains why, despite the increasing use of technology, not all questions have been answered. For its nature, history, and culture, for the presence of a boat, rowing is one of the most studied sports. But the pattern of exerted forces as a function of oars' angles is nonlinear and complex. Due to the interplay of anatomical and biomechanical elements and differences between crew members on the same boat, it seems unlikely that only one optimal profile is identifiable for all athletes. The bridge between performance and forces' characteristics of athletes is until under discussion [54]. Top performance entails that all working variables are close to their optimum, conceptualizable as a multidimensional space with a plateau. When everything works properly, the results are weak relationships between parameters, small ranges of values, and flat responses. This shows the challenges of coaching and researching [13] and makes it difficult to provide useful individual advice [55]. The importance of a single variable is shown only in a negative, asymmetric way because it is identified as a *cause* for a problem only when something is not working as it should. A technical detail or a single food cannot be assumed as *the cause* for the victory but maybe the problem *responsible* for a defeat. Different solutions have been proposed to these issues, once again demonstrating the need for integration of knowledge. The first is related to the role of environmental, organismic, and task constraints limiting the number of potential DOFs and producing coordination [56, 57]. Gravity, gender, anthropometry, muscular strength, power, equipment, or cadence influence sports technique. Along with all other natural constraints and sport rules, they limit the possible outcome but do not determine it. Moreover, some characteristics required from a certain performance do not account for all different individuals [43, 54, 58–60]. With the increased availability of technology and, therefore, of the number of variables that can be acquired when multiple features are measured together, there is a growing need for analytical techniques capable of simplifying data without losing information. High-dimensional data is reduced by principal component analysis (PCA), which looks for patterns and clusters. It represents a good meeting point between scientists' analytic approach and the holistic view of coaches [61, 62]. Open issues in this field are the definition of useful properties of the systems, the selection of testing methods [63] with the choice of experimental protocols [64, 65], detailed comprehension of the nature of motor variability, and the information it may provide about a relationship with performance, development of motor skills, recovery, and injury risk [41, 43, 46]. The dynamical systems approach incorporates a wide range of heterogeneous constraints [66], so the research for the athlete-specific optimum still is the *holy grail* of sports movement analysis [67].

3 A Point of Equilibrium

If Sport means movement, a living being entails the continuous search for static or dynamic equilibrium. This is the place where injury prevention [68, 69], motor control, fatigue, sports equipment, and final performance are closely linked together [70–72]. The sense of balance is a highly dynamic phenomenon [73] not dependent on just one organ. It is even more complex than the single five basic senses of hearing, sight, smell, taste, and touch. Systems and organs must cooperate in Mechanics and Biology's synergy to obtain equilibrium. Processing information coming both from the external (exteroception) and internal (proprioception) environments, quickly looking for an adequate solution, they are merged in the *mechanobiology* [74, 75]. Proprioception is decisive for equilibrium, posture, and gait but hardly graspable [76] because it requires a close and complex coordination of different apparatuses. The somatosensory network processes peripheral information coming from heterogeneous subsystems and relative positions of body segments. Muscles, tendons, skin, and joints contain mechanoreceptors able to record pressure, vibration, temperature, and pain. Proprioceptive information is crucial in building the final human balance [77–79]. For about a century, non-continuity of motion control has been stated when the brain converts the sensory data into appropriate motor solutions [37]. In fact, the process requires enough time to be properly performed. The muscular reference system has many dimensions. Possible solutions are not univocal. Simplifying strategies for the neuro computation are required. A powerful strategy is to cut information, making the continuous as discrete. It has been stated that our thoughts run at 40 Hz, but we can act at most about 10 Hz [80], meaning that about 25 ms are necessary to process brain data and 100 ms to operate the consequent motor control. All working receptors record and communicate discreetly. Each sensory system performs in its highly optimized range of frequencies to integrate data with others and provide adequate execution and timing [81]. Often it has not enough time to obtain and process all kinds of information necessary to execute complex anticipatory strategies. For this, these strategies are often very fast movements, as it happens in numerous disciplines [82]. The effect on the balance of tools compressing the skin (tapes, garments, clothes) is surprising because they may change the perceived feelings, proprioception, and balance, demonstrating, once again, the complexity of life [83–85]. Improvement of hemodynamic, reduction of stress in respiratory, cardiological, and metabolic systems reduced venous system's cross-sectional, activation of tactile mechanoreceptors, attenuation of swinging, and improved proprioceptive feedback couple with an improved equilibrium [86, 87]. Even a relatively low pressure exerted on legs makes athletes able to change and maintain an optimal position, increasing muscles' action and lowering unnecessary movements. It has no measurable negative effects on variables linked to perceived exertion or maximum voluntary isometric strength [87, 88]. Elastic and damping ability are other crucial qualities for athletes influencing their balance and position and even power, maximum strength, and technique. Passive vibrations activate many motor neurons acting on specific muscles [89], implying the risk of premature fatigue [90, 91]. The controversial debate on balance bracelets, with the partially explorable mechanisms supposed to underlie it, constitutes another example of the phenomenon's extraordinary complexity [92–94]. The brain must build absolute movements of head and body in the space for performing elaborated motor tasks. Data coming from proprioception and tactile receptors relate only to the internal environment, that is, relative movements and forces of body segments. Therefore, the balance of the head grouping labyrinths, eyes, and ears and making all these receptors work together must be somewhat privileged [82]. Much research stated the crucial role of head stabilization in different animals: migratory birds use the neck and whole body, athletes try to keep it in as much as possible in a controlled state while jumping or running [82, 95–98]. The labyrinth is an inertial, triaxial sensor equipped with semi-circular canals defining a local reference system without needing external support. It may not properly work under thermal stress, pressure compensation, or diseases [99, 100]. Due to the mix of inertial and gravitational accelerations, all inertial information may be ambiguous. The labyrinths move with the head local reference system to drift, provide illusory sensations, and fail to discriminate external environments' correct orientations. These ambiguities are figured out by combining visual and acoustic information. Vision and sense of sight are decisive [81, 101–105]. Even light sounds made by movements help the sensory feedback. Between actions and sounds, it is established a functional correspondence, so athletes and coaches are used to correlating force–time curves with noise, sometimes understanding complex parameters of movements that cannot be differently analyzed [106–108]. This has important implications for the management, selection, study, and optimization of any sports equipment requiring compromises between handling and precision, stiffness and elasticity, and being evaluated by personal feedback. Athletes are not machines and, in their judgment, may be influenced by age, experience, gender, technique, damping ability, motivation, prejudices, prize, fatigue, placebo effect, and stress. The ability to feel and manage mechanical vibrations relates to skill level and individual characteristics. Dissimilarities are magnified above certain thresholds of frequencies and amplitudes. The ability to use efficient strategies of rhythmic muscle contractions and regulation results in active damping, control of useful DOFs, improved stiffness of the muscle–tendon system, and, finally, a higher efficiency [71]. Sports equipment constrains the athletes and affects their perceptions determining the movement efficiency and capacity to provide accurate technical evaluations. Feelings and perceptions are unique to each body and partially incommunicable. So, the process of linking mechanical characteristics with personal feelings coming from many individuals and skills is a very challenging task [109]. The know-how is widely distributed among different expertise and not always univocal and objectified [110].

4 The Challenges of Biology and Physiology

The living beings are open systems of systems, interlaced networks, complex, looking for but far away from equilibrium, adaptive, time-varying, irreversible, and dissipative. They are multi hierarchical, operating over many scales of space and time, with memory and nonlinear feedback, the meeting point of many weak forces not always all clearly identifiable and none of which usually dominant. There is a complex and unique interaction between internal and external environments and a strong path-dependence unpredictable in advance. Systems of extraordinary complexity such as the brain, microbiome, and immune systems are tied together in the body [111], continuously and dynamically tuned by many bio-oscillators regulated by circadian, hormonal, seasonal, or ovulation cycles [112]. So, they are not graspable by simple static or taxonomic approaches. The biological equilibrium is contingent and temporary, both stable and flexible, enabling it to provide adequate responses to a continuously varying external stimulus [43]. The lack of universal rules to segment living organisms allowing simple causal analysis of their multiple and interlaced functions [113], the impossibility to isolate a single privileged causal level, and the variability in response to any given treatments [114–116] lead to biological relativity [117]. Fractal footprints and attractors are ubiquitously noticeable across many and different scales in neurophysiology, anatomy, physiological, and biomechanical behaviors [118]. Life is doubly unique because of its deterministic and historic-evolutionary nature [119]; the same results are achievable through very different pathways. Due to the great number of involved variables, links, and relations, special analytical techniques are required [120]. Historical-evolutionary mechanisms combined with unpredictable random events lead to unique living systems. So, the generalization of biological laws is difficult. When studying complex systems, there is a strong asymmetry between the inductions possible from available information and what can be explained after something has happened, giving the chance to forecast the future evolution from an actual observable state. Especially in the presence of dynamic and open systems, it is never possible to be sure to have all and really important information and to know the covering laws [121–124]. Looking at regularity and repetitions to predict the future is a very old problem even when faced in a modern perspective because it implicitly supposes that all is written in the past. However, this method needs sufficiently long historical series and the working variables to be known. It assumes that the DOFs are limited, and the system dynamics remain stable over time [125]. There are necessary conditions to win a competition, but the identification of sufficient conditions is a different matter. The way Biology and Physics are closely related is very complex and nonlinear. Retroactions, feedbacks, innumerable interactions, and dynamic processes not statically knowable are at work and difficult to dissect and understand. Simultaneous causes combine with multiple possible solutions. Paths of only a few biochemical reactions can link most pairs of metabolites. Local variations of concentrations could reach the whole network in a very short time. Few molecules take part in many reactions, modeling the network structure, and the experimentally observable functions. An open issue is the application of general properties to single individuals [115]. So, sweeping generalizations are rarely correct, and even when something *usually* occurs this does not mean that it must *always* happen [126]. Athletes play sport. They are living systems, open and dissipative structures looking for homeostasis and allostasis, continually negotiating matter, information and energy between inside and outside, where every chemical, physical, and thermodynamic equilibrium is temporary and contingent [118, 127]. Through hormones and other messengers, physical activity leads to extensive changes in cells, tissues, and organs, challenging the whole-body homeostasis and stimulating integrated, often redundant responses. Multiple and complex cellular networks are involved in this process where the muscle share information with other organs resulting in valuable effects on fitness and performance. Interference effects occur when training simultaneously for endurance and strength; skeletal muscles spread messages between different systems. The Biology of exercise requires an integrative attitude because of the upward and downward multiple and contemporary interactions between cells, genes, molecules, and organs [128, 129]. The integration and mutual adaptation produced during exercise find a powerful conceptualization in psychobiology [130]. As Poincaré already understood guessing the chaos in the apparently simple problem of the three bodies at the end of the nineteenth century, it is impossible to use simple cause–effect reasoning to study a system where numerous interlaced parts are simultaneously at work [131]. Recently, the coordination dynamics perspective has been used to explain the nonlinear interlinkages observed between different human subsystems. Disparate constraints operating at different levels lead to adaptations. This is possible thanks to configurations cooperating at various levels and shows practical applications to sports training [132]. No two bodies are equal, each one having personal and unrepeatable anthropometry and biomechanical characteristics, experience, skills, feelings, highly optimized technical movements adapted, and modeled after years of training, thousands of cycles, and, maybe, even from suffered injuries. Equipment is highly customized and sports-specific, heavily influencing how the athlete perceives the external world and acts. For a long time, biological models have been searched to explain the relationship between training and performance and why some athletes are faster than others [133]. Heterogeneous inputs such as neurotransmitters, hormone and substrate concentrations, ventilation rate, loads and pain, environments, and motivation play a role during exercise while the perception of physical effort is highly personal. Fatigue is an elusive multifactorial concept, unique and partially independent of the specific biological state. To be studied, it requires an interdisciplinary approach considering both mind and body [22, 133–135]. Molecular pathways and gene networks regulate the response to training with the initial conditions. The outcome is individual and should include genetic and epigenetic features, previous training history, and transient functional biological states [136]. The exact quantification of training loads is difficult. Complex open biological systems show interlaced interdependencies and sensitive dependence to initial conditions. Any given single external treatment may generate an unpredictable chain of consequences as it happens in diseases with historical–evolutionary development [22, 136]. Heart rate and blood pressure rise and fall along the days following many inputs, often remaining elevated long after the load is removed. Lactate level has a wide range among different athletes with inter- and intra-individual differences and may depend on the diet or previous muscle glycogen storage; not always a physiological steady state is maintained over time [22, 136, 137]. Different systems are involved in energy production in about the first 100 s after starting a maximal effort. Interestingly, many competitions or part of them fall in this range of time, challenging the possibility of using different strategies, or some combination of these. Activation times, passages between one system and the other, quantity and management of energy substrates, transients and recovery, pacing, and the performance model play a crucial, very complex role in training and race management [138]. The complexity of Biology implies that even new anatomical systems can be theorized. An example is the fascial system representing a continuum of soft, collagen-containing, connective tissue bridging micro- to macro-levels and allowing the integration between other different body systems. Myofascial tissue seems to affect the force transmission between muscles, thus influencing *mechanobiology*, athletic performance, and injury risk [139]. The fascia also works for physiological and metabolic homeostasis encompassing nerves and carrying hormones. It appears to play a key role in body regeneration [140, 141]. Nutrition represents the ideal concluding example for this section. The food comprises more than 26,000 known distinct biochemical components [142], and an ideal sports drink like cow's milk [143] has over 100,000 different molecular species. This is transformed and assimilated with a personal and unique ecosystem:

the microbiome. Food ingestion's order affects the subsequent serum glucose profile and shapes the hormonal profiles [144]. Many variables connected by countless links generate virtually all kinds of outcomes and correlations and deeply challenge our scientific knowledge in the field [145–149].

5 The Sports Environment: Opponents, Equipment, Field of Play, Weather, and Public

How to select the best wheat to optimize a crop yield? The question is not trivial because, in addition to cereal properties under investigation, innumerable external environmental variables such as soil composition, insolation, light, and water reaching the plants can interfere among them, overlapping the genuine differences between cereals. Nothing can be studied neglecting its ecosystem. The standard experimental approach is straightforward: try to make everything as homogeneous as possible and control everything supposed to play a role. It is assumed that only the investigated variables are at work while all the others remain inactive. So, any observed final effect is related only to the different used seeds. When evaluating the effects of a modification or intervention in sports, the same process is theoretically performed. So, all attempts are realized to manipulate only the working variables locking everything else, and it is assumed that all important information is known. Strong assumptions that all other things being equal (*cetertis paribus*) are made [150]. The most important external environmental factors such as heat, wind, altitude, temperature, humidity, visibility, the position of sun and shadow during the competition, vertical planimetry, playing surface, sailing regatta course, type and state of snow and ice have been understood and studied for a long time [151–153]. Athletes are trained to deal with these conditions [154]. Unfortunately, in reality, it is very difficult to solve these issues scientifically. Ronald A Fisher—a father of modern statistics—was aware that uncertainty and error are inevitable and consequently proposed to work with a *rigorously specified uncertainty* for making sense of the world and to acquire reliable empirical knowledge [155]. To his seminal ideas, we owe the concepts of randomization and double-blind in the sciences of life. However, in sport, it is not always possible to operate in this way. The outdoor field changes his status during the race. Environmental impact is crucial even in disciplines held indoor: temperature, humidity, light, and noise can affect the performance. How is it possible to randomize it? Quality and temperature of air, light and shadow, crowd presence, and the order in which the athletes are called to play a key role in the outcome [156, 157]. It is practically impossible to fully keep stable and equal for all athletes a track in a marathon, race walking, sailing regatta, downhill and cross-country ski, or bobsleigh and luge. Even the lanes of an athletics track, rowing basin, or swimming pool are not exactly equivalent to each other, so that they are assigned by merit or lot. The ice of the track deteriorates with the passage of blades, the wind changes direction, and the snow varies with sun exposure, daytime, and season. Bioclimatology heavily impacts the perception of fatigue; the light and the background color influence the aiming in the pentathlon, biathlon, and archery; the poor visibility affects the balance of the skier, as well as the waves, do with rowers, sailors, and surfers. During a test, it is normal that temperature and wind change. Furthermore, the number of competitions in a season is limited. For various reasons, the best athlete or team does not always win [31], and confirmations or rebuttals are not always possible due to different environmental conditions and races' unicity. It is difficult to fully perform the procedures orthodoxly required for tests in biosciences: randomizations, control groups, and double-blind protocols. Sometimes the very foundations of controlled experimentation are critical. In fact, often, the number of available top-level athletes is small, random control groups are impossible for practical or ethical reasons, and blind or placebo tests are unrealistic because everyone knows what he is doing and the equipment being tested. Athletes, coaches, and researchers are humans and have expectations and prejudices. Economic or other factors may be present, and not all boundary variables can be strictly controlled. It cannot be excluded that placebo and nocebo effects are at work [158]. A working strategy is inductive. The classic example is the Evidence-Based Medicine, where systematic research extracts the best available general evidence to be integrated with individual know-hows. A lot of data and proper statistics are required. This approach provides useful information in many areas, including injury prevention and treatment, stretching, and physical examination reliability [159]. Huge databases of competition data are widely available for sports analytics, and appropriate statistical tools extract general and transversal information looking for the best key performance indicators. Regression analysis is utilized when variables are continuous such as the official timings. Multiple linear regression has been tested and tuned: several variables are supposed independent, calibrated with proper coefficients, added together, and then used as input in systems of equations. The purpose is to estimate a predictive variable [48, 156, 160, 161]. Both fixed and random effects participate in forming these models, which can be organized as hierarchic or multi-level architecture. These characteristics tune models as linear, additive, and mixed. The observed values might vary from predicted values, and this difference permits evaluations and adjustments [50, 121, 162]. These tools are applied in many sports and for circumstances like the "home advantage" [163]. The outcomes are potentially interesting for researchers looking for all conceivable reasons of variability in test or race. For example, it is possible to investigate the effects of ground, snow type, and altitude separately from the bio-variability of human performance, so finding more or less remarkable stability of performances of top athletes and the eventual role of chance. Similar analysis and results are found in rowing [164], while interestingly, the predictability of performance is high when considering all athletes but low for top ones [51]. Other challenging results regarding the effect of the environment on performance come from sliding sports where top athletes' performance is variable and difficulty of different tracks, effects of ice softening and degradation, home advantage, and unpredictability of race outcomes are assessed [49, 165]. The multiplicity of applied pieces of knowledge and approaches to sports and physical activity is proven by the great variety of tools used for analysis [20, 64, 160, 166–171]. Considering all the competitions of 20 different Winter Olympics editions and excluding sports with subjective and esthetic judgments, home advantages were found only for few disciplines and not for others, contrarily to popular beliefs [161, 172]. Finally, it is worth mentioning that more or less consciously, other athletes, opponents, contestants, and competitors are an important environmental and unpredictable factor [173–175].

6 Testing: Where Integrated Competencies Meet

Testing and analyzing sports' performance is a matter of paramount importance but, at the same time, often a challenging issue. It is a sort of fractal process: each question opens other questions, and so on. The possibility to follow all normal procedures shows some limitations: careful assessments of internal and external validity should be made, the used surrogate endpoints must be properly validated and this is not always possible, laboratory and tests usually are more accurate and simpler to perform than those carried out in the field but not always representative, the number of possible tests with high-level athletes is often limited [64, 171, 176], the use of instruments on filed and worn on the body it is not always easy and may disturb the action, data are incomplete or cannot be used due to their poor quality or for technical issues, the time necessary for post-processing is long and not compatible with the needs of coaches and athletes [177]. In outdoor sports characterized by environmental variables, it is not always possible to evaluate the impact of field conditions on the outcome. Sometimes there is no way to make the competition field and track uniform in space and time and consequently fair for all athletes. Thus, in alpine skiing, the race numbers are drawn by lot between different merit groups, and the descent order of best athletes is reversed in the second heat. Enormous forces and torques arise in a fraction of seconds and are transmitted to external constraints across very small surfaces, thus generating transients and enormous pressures. External variability has multiple origins, and his measure and control are practically implausible over certain thresholds. In turn, there is an internal variability related to biological mechanisms. The human body continuously sets itself to respond to internal and external environmental changes: heart rate, body temperature equilibrium, flexibility and stiffness, production of force, and power are dynamically tuned. Perceived exertion of fatigue, circadian fluctuations, menstrual cycle, and jet lag may affect the results of the test and the evaluation of performance as well as of any biomarkers [112, 178–180]. So, the characteristics of the human systems entail special care to be studied [63]. Skeletal muscles play the role of agonists and antagonists at the same time, so that a motor task can be obtained in different ways. Available data for muscle activation are few and discrete as it occurs with electromyography. So, observations are inevitably limited to the "surface," the iceberg's tip, and the scientists try to infer the underlying processes [181]. This makes impossible to define the motor patterns univocally, so that some authors theorized the existence of a "motor equivalence," the possibility to use different coordinative movement patterns to produce similar outcomes functionally. Consequently, all different working subsystems are not experimentally separable, and some hidden phenomena are only speculated. To verify causal relationships, an ideal experiment should focus on one variable assuming all other constants and checking the effect on the outcome. A certain number of trials are needed to gain the reliability as a function of the selected parameter's type and consistency. In sports, this is often operatively difficult, if not impossible, for practical reasons [64] or because the movements under investigations are not simply graspable by single kinematics measures [59]. A limited number of feasible tests, gender bias because most studies are performed on males [64, 171], challenges in defining the proper predictors able to explain a performance [182] are all complications in applied sports research. Extraordinary issues arise when studying the interaction between crew members' coordination and a boat's performance in the presence of external and meteorological variables as it happens in rowing and sailing [183, 184]. When analyzing single sections of a race or a portion of data, there is the risk of losing critical information because each part of a performance is also a function of previous ones. Studying only a section might not be enough to understand and explain the global result [185, 186]. The Physics of sport is of extraordinary complexity when closely studied [187]. A crucial property of biological tissues is viscoelasticity, that is, the continuous deformation with time under constant loads. The stress decreases, and there is hysteresis [13]. As seen before, the human body is not rigid, has internal dynamics, redundant DOFs, not uniform density distribution, soft tissues, and wobbling masses. The external and internal mechanical information is read by receptors of the athletes and dynamically processed in a very short time by the Central Nervous System to provide suitable output, making stiffer or softer the whole body or its parts [82, 188]. It happens thanks to complex and partially unexplored feedback and control. For all these reasons, it is difficult to simplify and find solutions to differential equations systems. In sport, it is a well-known fact that not all the ideal solutions provided by Physics are applicable. Even well-trained top athletes are not able to use them on the field profitably [189]. This shows how it is necessary to consider biology's role, and everything is functional to humans. Adequate tools and models are required [9, 74, 160, 168–170], remembering the elusive nature of human features not all directly measurable and conceptualizable. Therefore, hypothetical and multifactorial constructs are used [190]. Even if close to the top performance, some limit configurations cannot be directly explored because of their instability and dangerousness. The definition and use of Key Performance Indicators (KPI) are becoming more and more widespread [191]. But it is necessary to remember that KPI refers to theoretical constructs. All models should be validated, wondering if simplifying and slicing the reality in preselected variables something important is being lost. This again emphasizes the importance of the integrated viewpoint. A theoretical approach allows sensitivity analysis, investigates the relationships between variables, and comes closer to understanding the causes than experimental studies looking for correlations. So, models and simulations are increasingly used to perform calculations, standardize the boundary conditions, and carry parametric tests without risks and at low cost. The optimum research suggests and hierarchies the most profitable development direction and drives towards appropriate experimental data acquisition. This process helps to adjust the simulations to adhere more and more to reality [192]. Unlike what happens in Formula 1 or in sailing America's Cup, this is difficult in other disciplines where the human body is the largest and heaviest part of the system. So, inertial, postural, muscular, kinematical, athletes' dynamical characteristics must be considered with related ability in motor control [193, 194]. The simulations of athletes, equipment, environment, and opponents are limited by the systems' biological and complex nature with many DOFs, and the internal dynamic is not fully defined. Body geometry reconstruction [195], individual features, muscle models, wobbling masse representing soft tissue, rigidity and viscoelasticity, inverse dynamics, interface with external surfaces, and inertial parameters are examples of challenging issues. The system is path-dependent, self-adapting, continuously fatiguing and recovering, characterized by continuous accumulation and processing of memory, and exceptionally sensitive [6, 196]. So, often broad generalizations are unserviceable, and it is more effective to aim at specific improvements of single top athletes. Contingent and highly customized answers are provided for technique, training, injury prevention, and other details limiting the performance. Finally, a key important role is played by the competition formats, which often, even in the Olympic Games, are intentionally designed to shuffle the cards making the most exciting and unpredictable results but sometimes penalizing the most deserving athletes in favor of the show.

7 Conclusion

Western thought history is characterized by the attempt to tie universal to particular, multiple to unitary, necessary to contingent, ideal to real, objective to subjective, and absolute to relative. Modern Western science was born and developed thanks to the obsession for unbiased measurements. Plato stated that the world of ideas is objective and general. In contrast, life's world is subjective and singular because body and senses provide only personal, contingent, and deceptive sensations. In *the Assayer*, Galileo Galilei claimed that heat, color, flavor, and smell are not objective, *essential* qualities of the bodies but subjective, *sensible* impressions due to our organs. He concluded that *only what can be counted is important: we must measure what is measurable, and make measurable what is not*. In this way, Galilei paved the way for modern redutionist science. Western Medicine has been thinking for at least 25 centuries about jumping between classes' properties to those of individuals. Descartes objectified the body, making mechanism the organism, a sum of parts to analyze using Physics' approaches like dynamics or hydraulics, so opening the possibility to use a Newtonian method to study the living beings and leading to the foundation of modern Medicine and Bio-sciences. The body includes organs, each with objective and measurable features studied by different specialists and producing separated branches: cardiology, orthopedics, ophthalmology, pulmonology, immunology, dermatology, surgery, and so on. The discovery of pathogens whit the correspondence of a bacterium with a disease at the end of the XIX century, and modern genetics in more recent times, further strengthened the reductionist approach where each discipline generates its own knowledge, detached from the others. In the hospital, the sick person becomes a carrier of organs or pathologies and is referred to specialists and diagnostics based on specific symptoms. This anatomical-functional taxonomy has brought extraordinary results for all to see but moved away from the holistic knowledge dividing it into competencies and sectors. The same happened in sports sciences shaped on life sciences: physiology, sports medicine, biomechanics, performance and match analysis, analytics, training, strength, and conditioning, nutrition, vision, psychology, talent identification, coaching, sports equipment and technology research, the study of technical and tactical demands, analysis of Key Performance Indicators, team management, performance planning, neurosciences, and Big Data are all generally recognized as disciplines to be studied for their contribution to the final outcome but hardly tied together to paint an overall picture. In modern sport, this approach has led to enormous progress, as shown by human performances' evolution over time. However, all these different pieces of knowledge, far from being incompatible, require a deep integration to work properly. Sometimes science is the hostage of its method, the mathematical-quantitative process adopted to produce ideal objects used to interpret and comprehend the real world. Considering the athlete and the sports performance in isolation, the purpose, and intention that make each gesture an adequate response to a given situation is lost. The performance is not the product of pre-existing structures but rather the result of unpredictable choices made in a continuous adaptation of the external and internal worlds. As Antonio Machado poetically warned: *there is no way. Walking makes the way*.Having highlighted in the introduction the importance of *integration*, now let briefly dwell on the term *knowledge*. In sports, the know-how is widely distributed among different expertise such as coach, trainer, physiotherapist, analyst, medical doctor, engineer, mechanic, ski man, sports equipment manufacturer, and—ultimately—the athlete. This know-how is not always objectified. It is impossible to teach someone to swim or to ride a bike only in words. Sensations, balance, feedback, and execution technique are strictly personal for each of us and can be transmitted and learned only through complex processes of examples, imitations, trials, and errors. In the 1950s, it was introduced the concept of *tacit knowledge*, the kind of implicit, non-codified knowledge we are not aware of and therefore unable to explicit [110]. It is indefinable know-how between Science and Art based on complex interactions of cognition and memory [197], difficult to transfer but—nevertheless—possibly resulting in significant competitive advantages [198]. Everyone involved in sports should challenge these issues minding that they cannot be separated from each other beyond a certain level. Here is the integrated approach's beating heart: a diversified group capable of disparate and dynamical answers. In modern sport, different professionals' competencies are required to support the Athlete and the Coach, and a global view should be recommended. It is not always possible to understand, calculate, simulate, predict, and control all that happens. Limitations lay on different fundamental reasons: insufficient knowledge of governing laws and initial/boundary conditions; poor understanding of variables distribution and the underlying dynamics; the nature of the system [3, 29]; too many DOFs [125, 199]; not separability between observer and observed; all other things being equal assumptions [150]; historical-evolutionary nature combined with random events; an inextricable mixture of chaos and noise. Complex living organisms show all these features and are open, challenging issues [200]. The study of the emergent behavior at different scales may be a target for the future, as well as the comprehension of how the system dynamics are governed by the constraints acting at various orders and levels. Space and time patterns may exhibit corresponding but, at the same time, different behaviors. As it happens in other biological groups featured by dynamic order emerging from physical principles, random perturbations, and simple rules mixed, team sport performance analysis entails complex interactions of deterministic and evolutionary behavior, leading to still an unsolved problem [16, 132]. Sport embraces many different and pluri-contextual pieces of knowledge, but a Grand Unified Theory of sports performance is still not available. Some researchers even doubt the possibility of achieving unified theories in complex adaptive systems [201]. Frontiers remain to be explored [57], demonstrating, once again, the key role of knowledge integration and why the sport Sciences are an extraordinary field of play.

Integrated Sport Sciences in 2050

According to a famous and provocative definition, playing a game is *a voluntary attempt to overcome unnecessary obstacles according rules to forbid the use of the most efficient means* [202]. Adding the need of body movements, for Sport is the same. So, room for improvements will always exist because sport is made of athletes, opponents, rules, equipment, environments, and records. The formers are, at the same time, the less and the more variable element. The less because in the next years the human body will reasonably remain the same, the more because developments in fields such as neurosciences, artificial intelligence, training, food, and applied technology are unpredictable. Sports rules, equipment and records will depend on how the show and the business will develop. The inclusion of eSports is a challenge for the future. But beyond certain limits it is not possible to predict the course of open, adaptive, and complex systems. And Sport is done by women and men with their emotions, passions, weaknesses. So, it will change and evolve to likely remain that exciting and unpredictable phenomenon we all know and love.

Core Messages

- Due to its unique characteristics, sport represents an extraordinary challenge for the limits of human physical performance and scientific knowledge.
- The top performance is a multidimensional construct at the intersection between Physics, Chemistry, and Biology, so a multidisciplinary and integrated approach is necessary.

- The uniqueness of each body and the distribution of sports know-how among diverse expertise make the knowledge partially implicit, non-codified, and non-transmissible.
- In open, complex, adaptive systems, the relationships between parts and outcome can be speculated within certain assumptions, and sometimes it is only possible to set intermediate, surrogate endpoints to be adequately validated.
- Science of complexity and networks, integrated biology, Big Data, models, and modern approaches brought several answers to old questions in sports and opened new challenging frontiers.

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