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Constraints on the Complete Optimization of Human Motion

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Abstract

In sport and exercise biomechanics, forward dynamics analyses or simulations have frequently been used in attempts to establish optimal techniques for performance of a wide range of motor activities. However, the accuracy and validity of these simulations is largely dependent on the complexity of the mathematical model used to represent the neuromusculoskeletal system. It could be argued that complex mathematical models are superior to simple mathematical models as they enable basic mechanical insights to be made *and* individual-specific optimal movement solutions to be identified. Contrary to some claims in the literature, however, we suggest that it is currently not possible to identify the complete optimal solution for a given motor activity. For a complete optimization of human motion, dynamical systems theory implies that mathematical models must incorporate a much wider range of organismic, environmental and task constraints. These ideas encapsulate why sports medicine specialists need to adopt more individualized clinical assessment procedures in interpreting why performers' movement patterns may differ.

A compelling challenge facing biomechanists working in sports medicine and the sports and exercise sciences is that of identifying optimal techniques for the performance of a wide range of motor activities. In this way, their work with movement scientists could lead to improvements in sport performance while preventing the occurrence of injuries through dysfunctional movement patterning. In tackling this challenge, biomechanists have typically resorted to forward dynamics analyses or simulations, in which sets of ordinary differential equations derived from Newtonian and Lagrangian mechanics are used to calculate and propose optimal movement solutions.[1] In a forward dynamics analysis, input variables are typically composed of the applied forces or net joint torques acting on the neuromusculoskeletal system and the calculated output variables are kinematic data describing the motion of the component parts (i.e. torso and limb segments) of the neuromusculoskeletal system. The accuracy and validity of these output variables are largely dependent on the complexity of the mathematical model used to represent the neuromusculoskeletal system.

There is a dichotomy of opinion in the literature as to the requisite complexity of mathematical models required for meaningful forward dynamics analyses. On the one hand, Hatze[2] suggested that, to identify the complete optimal movement solution for a given motor activity, it is necessary to use a highly sophisticated mathematical model. In contrast, Alexander[3] argued that attempting to reproduce the complexity of the neuromusculoskeletal system in a mathematical model is a futile exercise and the generation of simpler (i.e. more abstract) models should be given preference. The general consensus of opinion, however, is that the complexity of the mathematical model used to represent the neuromusculoskeletal system should be governed by the research question to be answered and the analytical goals of the investigator.[1,4,5]

In this article, we critically analyse mathematical models used in forward dynamics analyses or simulations and discuss how applications of dynamical systems theory in the movement sciences might influence how the process of optimization may be conceptualized by biomechanists working in sports medicine and the sports and exercise sciences. We begin by providing a brief overview of mathematical models currently used to represent the neuromusculoskeletal system and we outline the relative merits of simple and complex mathematical models. Next, we introduce some key concepts of dynamical systems theory, applied to the human movement sciences, with specific reference to Newell's model of constraints.[6] We then discuss the limitations of current mathematical models of the neuromusculoskeletal system from a dynamical systems perspective and highlight the potential of more sophisticated mathematical models for optimizing movement.

Contrary to some extant views in sports and exercise biomechanics, we discuss why completely optimal movement solutions for specific motor activities, generalizable to all performers, may currently be inaccessible. We evaluate the argument that a complete optimal solution for a given motor activity requires mathematical models that incorporate a much wider range of organismic, environmental and task constraints. We then outline a research strategy for identifying the constraints most influential in shaping and guiding emergent patterns of movement coordination and control. To conclude, we discuss the potential implications of a dynamical systems approach for practitioners in science and medicine and the assessment of functional or dysfunctional movement patterns.

1. Mathematical Models of the Neuromusculoskeletal System

Current mathematical models used to represent the neuromusculoskeletal system range from the very simple to the highly complex. Simple mathematical models are generally characterized by a limited number of rigid body segments, which are of a standardized length and have uniform mass distribution. These body segments are typically interconnected by frictionless pin joints and are operated by no or very few muscles. An example of a simple mathematical model and its application was proposed by Alexander[3] in descriptions of walking and jumping. The model for walking (figure 1) consisted of a massless leg and a point mass at the hip and the model for jumping (figure 2) consisted of a massless thigh and shank and a point mass at the hip. The model for jumping also included a knee extensor muscle that was assigned realistic force-velocity properties. Despite the abstract nature of these models, they were instructive in providing basic insights such as why normal

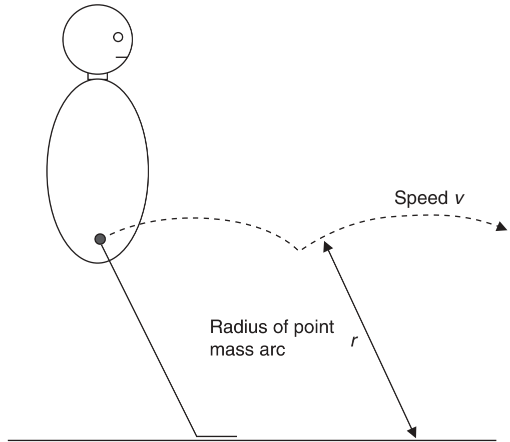

Fig. 1. The simple 2-segment model of walking (reprinted from Alexander,[3] with permission from Elsevier © 1992).

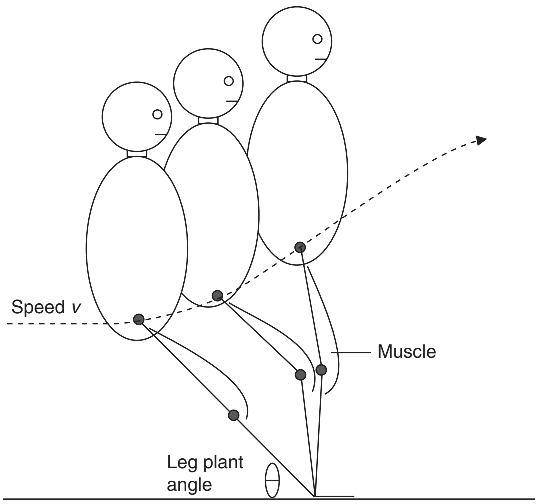

Fig. 2. The simple 3-segment model of jumping (reprinted from Alexander,[3] with permission from Elsevier © 1992).

walking speeds are limited to approximately 3 m/s, and why long jumpers run up faster and take off using larger leg plant angles than high jumpers.

Complex mathematical models, in contrast, generally include many rigid or deformable body segments and muscle groups, which have their own unique individual-specific anthropometric (geometrical and inertial) and strength characteristics, respectively. For example, Hatze[2,7-10] described a 17-segment mathematical model of the neuromusculoskeletal system complete with 42 mechanical degrees of freedom and 46 individual muscle groups. The 17 body segments were as follows: the abdomino-thoracic segment, the head-neck segment, left and right shoulders, upper arms, forearms and hands, the abdomino-pelvic segment, and the left and right thighs, lower legs and feet. Figure 3 shows the 42 generalized coordinates ($q_1, \ldots, q_{42}$), which defined the configuration of the mathematical model in space, and the 17 local, segment-fixed coordinate systems (x_1, y_1, z_1) … (x_{17}, y_{17}, z_{17}), which were located at the centre of mass of each segment. The 46 individual muscle groups required neural control time histories as input variables that could be adjusted until the required limb and torso movements were produced (see Hatze[11] for a comprehensive review). To personalize the equations of motion, a battery of 242 individual-specific anthropometric measurements, and a variety of isometric and isotonic strength measurements, were required.

This sophisticated mathematical model of the neuromusculoskeletal system took account of gender differences and even the specific morphological characteristics of obesity and pregnancy in humans. Hatze[7] claimed that this mathematical model was adequate for investigating gross human movement, as in his weighted-boot study.[12] Although it has often been reported[13] that Hatze used the full neuromusculoskeletal model in his simulation of the

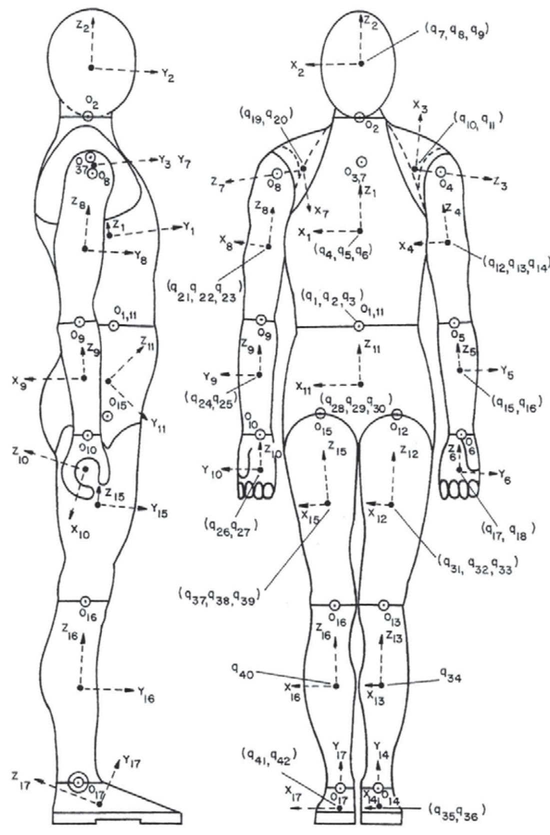

Fig. 3. Lateral and anterior view of the 17-segment mathematical model (reprinted from Hatze,[7] with permission from Elsevier © 1980).

long jump,[14] joint torques were optimized in that study without using the full muscle model.[15]

1.1 Model Sophistication

Exactly how sophisticated a mathematical model has to be is a contentious issue for sport and exercise biomechanists. In the past, simple 2-dimensional (2-D) or planar models have been popular because of their mathematical convenience and computational simplicity.[16] Indeed, due to the comparatively small number of outcome scenarios with simple mathematical models, it is easier to locate global optima with these models than it is with more complex mathematical models. The latter typically require the use of more advanced optimization techniques, such as simulated annealing,[17] to decipher global optima from local optima. Another advantage of using simple mathematical models is that they provide results that are more easily interpretable by clinical practitioners, coaches and athletes.[15] Simple mathematical models, such as those outlined by Alexander[18] for walking, running, jumping and throwing, have been useful for providing basic mechanical insights and developing fundamental principles of human movement. Indeed, it has been argued that the most fundamental understanding often comes from the simplest of models[19] and that establishing cause and effect is often easier with simpler models.[3]

More recently, however, more complex 3-dimensional (3-D) or spatial models have gained popularity as a result of advances in computer technology and the advent of automated equation-generating programs such as AUTOLEV, NEWEUL, MACSYM, DADS, ADAMS and SYMBA.[20,21] Since most human movements are not planar, 3-D models are more realistic than 2-D models.[10] Complex mathematical models can be considered superior to simple mathematical models as they putatively enable individual-specific optimal movement solutions to be identified *and*, with the use of appropriate constraints during the modelling process, can also provide basic mechanical insights for developing fundamental principles of human movement.[13] Due to the wide range of constraints on movement behaviour, and contrary to some reports in sport and exercise biomechanics,[12] it is argued that the identification of the complete optimal movement solution for a given motor activity is currently not possible.

In section 2, we elucidate these arguments. We provide an overview of some key concepts of dynamical systems theory, such as 'self-organizing optimality', and elaborate why it is currently not possible to identify the complete optimal movement solution for a given motor activity. To support these arguments, we outline a constraints framework[6] that could, in principle, enable the complete optimal movement solution for a given motor activity, at any given time, and for any given individual, to be identified.

2. The Role of Pleiotropy and Degeneracy in Complex, Dynamical Neurobiological Systems

Traditionally, the human neuromusculoskeletal system has been conceptualized as a deterministic, information-driven machine finitely controlled via integrated sensory feedback loops by a capacity-limited microcomputer acting as the brain.[22] In traditional deterministic experimental paradigms, a major aim is the reduction of uncertainty for examining movement behaviour of such 'closed systems'. From this philosophical standpoint, legitimate scientific enterprises include the empirical identification of 'optimization mechanisms' of behaviour[23] (e.g. how some individuals achieve reliable movement performances over repeated trials). This perspective, popularized by scientists in the physical sciences, engineering and robotics, has been questioned in the human movement sciences by a biophysical theoretical orientation in favour of conceptualizing neurobiological systems as complex, nonlinear dynamical systems. From this relatively new perspective, the human neuromusculoskeletal system can be described as an integrated network of co-dependent subsystems that are composed of many interacting component parts, or degrees of freedom, operating over multiple scales of space and time.

It has become apparent that complex neurobiological systems are *pleiotropic* and *degenerate* with their multitudinous degrees of freedom having the capacity to adopt different roles in satisfying the different constraints on their behaviour. That is, such systems are versatile and not highly specialized. Their inherent *pleiotropy* is based on their capacity to use their many degrees of freedom in different roles. Pleitropy instills inherent back up in metastable complex systems (systems that switch continuously between states of stability and instability) by providing a number of different options to support the search for alternative behavioural solutions. Conceptualizing neurobiological systems as complex suggests that inherent pleitropy could support a range of alternative outcomes from the dynamical interactions of system components (e.g. muscles or joints in a human movement system or the players in a sports team). For example, characteristics such as complexity and pleitropy make it challenging to identify 'the' most appropriate solution for a performer in sport, requiring a re-evaluation of decision-making behavior in dynamic performance contexts. Characterizing attacker-defender interactions in team games as a complex system implies that inherent pleitropy could make it hard to predict decision making of players, since there could be a range of alternative outcomes from the dynamical interpersonal interactions of system components.

Degeneracy refers to the capacity of structurally different components of complex neurobiological systems to achieve different outcomes in varying contexts, and is exemplified by the networks existing at different levels of human movement systems including molecular, genetic, neural and musculoskeletal.[22] Degeneracy in complex biological systems provides the neurophysiological basis for the diversity of actions required to instantaneously negotiate information-rich, dynamic environments, as well as providing a huge evolutionary fitness advantage.[24] In recent years, questions have arisen over the efficacy of descriptions of human movement systems as complex systems with many redundant degrees of freedom, inspired by the insights of Bernstein.[25] The term 'redundancy' is a more relevant descriptor for physical and engineering control systems, generally used in relation to the strategy of duplicating system components as a back-up in case of system failure.[24] Redundant systems provide similar outputs from different components. Biological systems are not structured in the same way as mechanical or electronic systems and there are different solutions for ensuring robustness and adaptivity in animate systems. In this respect, degeneracy is a better descriptor of biological systems than the term redundancy.

A good example of degeneracy in biological systems is during sensory deficits, where the use of brain imaging techniques has revealed that the visual cortex in blind humans can be activated during tasks requiring attention to auditory and haptic information sources. These findings have demonstrated how compensatory adjustment in degenerate nervous systems can result in the pickup of novel information sources for guiding movements.[26] Additionally, it is now well established that motor equivalence, or the ability of different patterns of neuromuscular activity to achieve specific movement outcomes, can provide the degenerate human movement system with a distinct advantage through the contextual adjustment of actions to information-rich environments, typically needed in many performance environments. Degeneracy of human movement systems provides the capacity to trade-off specificity and diversity of actions under changing task constraints, influencing the emergence of decision making and action.

Characteristics such as complexity, pleitropy and degeneracy make it challenging to identify a 'common optimal movement solution' for all performers, requiring a re-modelling of movement behaviour in dynamic performance contexts. In complex neurobiological systems, spontaneous pattern formation among degrees of freedom emerges, not through the intervention of an external regulating agent, but through generic processes of physical self-organization.[27-29] As neuromusculoskeletal systems are 'open' systems – that is, they are stable yet far from thermodynamic equilibrium – they constantly engage in energy transactions with the environment, encouraging orderly and stable relations to form between their component parts.

At the level of muscular-articular links,[30,31] the number of biomechanical degrees of freedom to be regulated can effectively be reduced by the spontaneous formation of functional muscle synergies[25,32] or coordinative structures.[33,34] Tuller et al.[35] defined a coordinative structure as "… a group of muscles often spanning several joints that is constrained to act as a single functional unit." A characteristic of a coordinative structure in pleiotropic and degenerate neurobiological systems is that, if one of the component parts introduces an error into the common output, the other component parts automatically make compensatory adjustments to minimize the effect of the original error.[36,37] Furthermore, the 'soft assembly' of coordinative structures is a feature of neurobiological complexity, affording great flexibility and adaptability as individual muscles can participate in different coordinative structures on different occasions.[38,39] These task-specific structural units can be modulated or tuned by perceptual information to accommodate sudden, unforeseen changes in task demands.[40,41]

2.1 Constraints on Neurobiological Complexity

The formation of coordinative structures or functional muscle synergies is dependent not only on processes of self-organization, but also the constraints imposed on specific neuromusculoskeletal systems.[6,25,42-44] The constraints concept has a rich tradition in theoretical physics, evolutionary and theoretical biology, and mathematics. In general, constraints are internal or external features that limit the number of possible configurations that complex systems, such neurobiological systems, can adopt. Constraints define the boundaries within which human neuromusculoskeletal systems must operate and, therefore, shape the emergence of patterns of coordination and control. The problem for neurobiological systems with a vast multitude of degrees of freedom is to constrain the number of micro-components involved in system behaviour, and in the movement sciences this has been addressed as 'Bernstein's problem'.[36] According to the influential framework of Newell,[6] there are three categories of performance constraint – organismic, environmental and task – that coalesce to channel and guide patterns of coordination and control produced by the neuromusculoskeletal system (see figure 4). It is important to note, however, that these categories of constraint identify the source, rather than the actual nature, of the constraint.[45]

Newell[6] considered organismic constraints to be those constraints that are endogenous to individual neuromusculoskeletal systems. Organismic constraints can be subdivided into structural and functional constraints. Structural organismic constraints tend to be physical constraints that remain relatively constant over time and include: height, body mass and composition; genetic make-up; the anthropometric and inertial characteristics of the torso and limbs; the number of mechanical degrees of freedom and ranges of motion of articulating structures; the fast- and slow-twitch fibre composition; angle of pennation, cross-sectional area, and the activation and fatigue characteristics of skeletal muscle; and so on.[46] Functional organismic constraints that have a relatively faster rate of change, on the other hand, tend to vary quite considerably over time and can either be physical or psychological. Important functional organismic constraints include intentions, emotions, perception, decision-making and memory. Perhaps the most prominent and influential organismic constraint that can shape movement coordination is the intentions of the specific individual under scrutiny.[29]

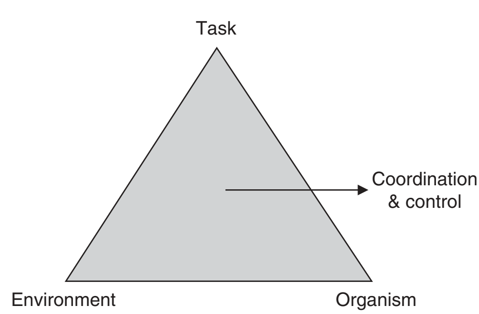

Fig. 4. Newell's[6] theoretical model of interacting constraints.

Environmental constraints were defined as exogenous to the neuromusculoskeletal system. They tend to be constraints that pertain to the spatial and temporal layout of the surrounding world or the field of external forces that are continually acting on the neuromusculoskeletal system. Environmental constraints are typically more challenging to manipulate during experimentation. Examples of environmental constraints include ambient light and temperature, altitude, acoustic information, ubiquitous gravitational forces and the reaction forces exerted by *terra firma* and other contact surfaces and apparatus. More recently, Newell and Jordan[47] proposed that environmental constraints encompassed any physical constraint beyond the boundaries of the organism. Implements, tools or apparatus, originally categorized by Newell[6] as being tasks constraints, were classified under the category of environmental constraints under the revised framework.

Task constraints, as the name implies, are specific to the task being performed and are related to task goals and rules governing performance contexts as well as boundaries and instructional constraints imposed on performers. The constraints of the task operate as an umbrella over all other constraints in influencing what patterns of coordination and control are produced.[6,42,44] The relative impact of task constraints on the neuromusculoskeletal system is largely dependent on the motor activity being performed. For example, in many ontogenetic motor activities, task constraints set certain limits or boundaries to patterns of coordination and control. In many phylogenetic motor activities, by contrast, task constraints do not inhibit or restrict patterns of coordination and control to any great extent.

One of the most profound conceptual implications of Newell's model of constraints[6] is that optimal patterns of coordination and control emerge from the unique confluence of constraints impinging on individual neuromusculoskeletal systems through a process referred to as 'self-organizing optimality'. The concept of self-organizing optimality is tantamount to the 'constrained optimization' concept advanced in the theoretical and evolutionary biology literatures by, amongst others, Maynard Smith[48] and Staddon and Hinson.[23] Constrained optimization states that the behaviour of a biological system at any time will always be optimal for the specific confluence of constraints acting on the system, or as Mazur[49] stated, the system will "always do the best it can." An important point for sport scientists and clinicians to note, however, is that even though the pattern of coordination and control produced by the neuromusculoskeletal system might be optimal in relation to the immediately imposed constraints, the performance outcome could still be suboptimal or unsuccessful.

It is important to note that models of 'constrained optimization' are harmonious with concepts from non-linear dynamics, such as emergence and self-organization under constraints, and capture the adaptability and compensatory variability of human actions required in dynamic performance contexts such as sport and exercise. Importantly, this modelling trend fits well with data from recent studies revealing the inherent degeneracy of biological movement systems.[24,50] From this constraints-led perspective, optimal motor performance, therefore, could be better defined as an individual attempting to satisfy the unique combination of interacting constraints impinging on him/her at any given point in his/her development. From this theoretical standpoint, optimization may be better considered from the perspective of the individual under scrutiny and the confluence of constraints impinging on that individual, not some abstract, external reference or independent criterion.

Since the constraints imposed on an individual dynamical movement system can fluctuate continuously over time, the optimal pattern of coordination and control for any given motor activity can change accordingly. Furthermore, as the conscious and sub-conscious interpretation of these constraints is dependent on the intrinsic dynamics (i.e. preferred states of coordination and control based on neuromusculoskeletal system architecture, genetic composition, previous task experience, emotions, etc.) of each individual under scrutiny, optimal patterns of coordination and control for any given motor activity will always be individual-specific.[6,45] Inter-individual variations in movement patterning may, therefore, be interpreted as adaptive behaviour on the part of dynamical neurobiological systems as they exploit surrounding constraints to shape the functional, self-sustaining patterns of behaviour that emerge in specific performance or rehabilitation contexts. Clearly, these theoretical insights from neurobiology have important implications for sport and exercise biomechanists working towards the complete optimization of human movement.

3. Modelling the Neuromusculoskeletal System: A Dynamical Systems Approach

It could be argued that, from a dynamical systems perspective, a major reason why sport and exercise biomechanists have been unable to identify the complete optimal solution for a given motor activity is that mathematical models of the neuromusculoskeletal system currently do not take into account the full range and uniqueness of the constraints impacting on each individual. Indeed, as Newell[51] pointed out, "…optimization modelling has been largely confined to a consideration of mechanical constraints. However, mechanical constraints are clearly not sufficient criteria for optimization in biological systems, although they represent an important beginning to this effort." Newell's[51] analysis suggests that sport and exercise biomechanists working towards the complete optimization of human motion need to include a much wider range of organismic, environmental and task constraints in their mathematical models of the neuromusculoskeletal system because "… in principle, these constraints will determine the optimal coordination and control for a given individual in a given activity." These ideas are reminiscent of criticisms of the 'adaptationist' stance in evolutionary biology which surmises that the constraints of natural selection are so powerful that a biological organism can be 'atomized' into traits or structures, each of which can be adapted independently of the whole system. This theoretical perspective has been criticized for being too reductionist. That is, it has inappropriately reduced complex systems in nature to a series of discrete objects each operating under a narrow range of constraints, when actually a wide range of constraints are considered to interact in shaping the evolutionary development of the whole organism.[52]

In recent times, because of advances in technology and increased computer processing power, the number of constraints (or parameters in biomechanical modelling parlance) that can be incorporated into mathematical models of the neuromusculoskeletal system has grown significantly. Organismic constraints have begun to be included in some models, for example in the form of individual-specific anthropometric (geometrical and inertial) parameters,[53,54] strength parameters,[55,56] soft tissue movement (so-called 'wobbling' masses),[57,58] and limits to joint ranges of motion.[59,60] In the highly sophisticated mathematical model of the neuromusculoskeletal system described by Hatze,[2,7-10] a wide range of structural and functional organismic constraints has been incorporated into the mathematical model of the skeletal, muscular and neural subsystems. The most advanced of these was the model of the muscular subsystem[7,9,61,62] designed to closely mimic the behaviour of real muscle tissue. Indeed, according to Hatze[11] this muscle model fully accounted for the dynamics of sarcoplasmic calcium release upon stimulation, the non-linear active state dynamics, the non-linear dynamics of motor unit recruitment, and the highly non-linear contraction dynamics (i.e. force-velocity and length-tension relationships).

Environmental constraints have also been included in the form of aerodynamic forces,[63] contact surfaces[64] and apparatus.[65] An important addition to the literature has been the mathematical model for the control of interceptive actions introduced by Beek et al.[66] Previously, Beek and Beek,[67] acknowledging the work of Newell,[6] argued that: "In many instances, the first requirements for successful actions are not exclusively in a sufficiently large delivery of either force or energy, but also, and foremost, in an optimal guidance of force and/or energy on the basis of perceptual information." However, attempts to mathematically model the integration of perceptual information and movement have been scarce and they have generally been limited to 'short route' models that do not address how perception-action patterns might be constrained by the dynamical properties of the neuromusculoskeletal system. Beek et al.[66] reportedly overcame the phenomenology of existing 'short route' models by developing a 'long route' model where the dynamics of the sensory, neural and musculoskeletal subsystems were integrated to reproduce interceptive actions (figure 5). Their model consisted of neural network architecture for the online generation of motor outflow commands, based on time-to-contact information and information about the relative position and velocities of hand and ball. Beek et al.[66] showed their mathematical model to be consistent with both behavioural and neurophysiological data.

Although not included in the actual mathematical model of the neuromusculoskeletal system, task constraints have been included during the simulation process, generally in the form of an optimality criterion or a specific cost function that must be maximized or minimized. These objective measures describe either the task goal or an aspect of performance that is strongly related to the task goal. Whereas other optimality criteria or cost functions, such as smoothness, accuracy, speed, minimum fatigue and minimum sense of effort have been used,[68-70] energy consumption or, more precisely, energetic efficiency,

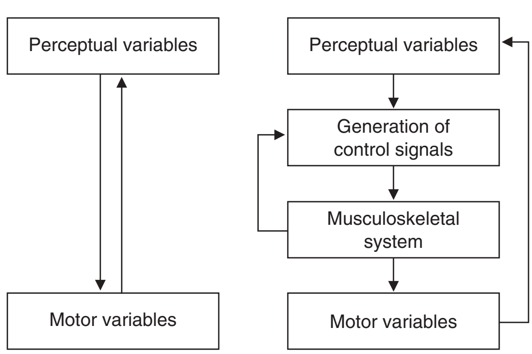

Fig. 5. 'Short route' and 'long route' models of the control of interceptive actions (reproduced from Beek et al.,[66] with permission from The Royal Society).

has typically been the chief optimality criterion or cost function in the biomechanical modelling of human motion.[71] While the optimality criterion or cost function can be viewed as the main, overarching task constraint, there are other nested task constraints that need to be incorporated. However, one of the problems with contemporary simulation approaches is that they are inflexible and generally rely on only a single optimality criterion or cost function for each simulation. If the simulation of human movement is unable to take into account a wider range of interacting task constraints, it runs the risk of becoming merely an academic exercise with limited practical relevance to performance in dynamic environments.

Another task constraint that has featured in the modelling literature has been that of consistency of technique or, more specifically, robustness to perturbation. For example, Wilson et al.[60] undertook an optimization of a running jump for height that, along with angular momentum at take-off and joint range of motion, included robustness to perturbation of activation timings as a constraint on performance. It was shown that the optimization that included all three of these constraints produced a simulated jump performance (1.99 m) that was similar to a high jumping performance (2.01 m) recorded from the athlete. However, when the robustness to perturbation constraint was removed, the simulated jump performance increased to 2.14 m, suggesting that stability of performance is an important consideration even in motor activities that require maximal effort. Wilson et al.[60] acknowledged the work of Newell,[6,51] recognizing the ubiquity and interplay of a multitude of constraints in the self-optimization of emergent patterns of coordination and control across the lifespan.

In describing performance robustness, along with global and local optima, Yeadon[72] invoked a landscape metaphor analogous to the 'attractor' landscape that features prominently in the dynamical systems literature on motor control, learning and development.[73] Yeadon[72] stated that: "The search for an optimum can be likened to the search for the highest mountain peak in a given terrain: an optimization routine may find a local rather than a global optimum – the top of a foothill rather than the summit of the highest mountain. On the other hand, the routine may be successful in finding the top of a singular pinnacle that stands on a narrow base high above the surrounding terrain. Even if this is the global optimum it is a summit that should not be attempted, since any small location error will land on a low terrain. In other words, if there is an optimum technique in javelin that is surrounded by poor performances, it is a poor strategy that strives for this in the distant hope that everything will come right on one of the attempts. The likelihood is that all performances will be poor. A better strategy may be to find a high hilltop with a large plateau so that points even some distance away are high. There is much to be said for consistency when competing.''

3.1 Identifying Key Constraints: An Opportunity for Interdisciplinary Research

Having established the need to include a wider range of constraints into mathematical models of the neuromusculoskeletal system for the purpose of identifying the complete optimal movement solution for a given motor activity, a key question is: which constraints are most influential in shaping and guiding patterns of coordination and control?

Although, as we have discussed, it is the confluence of organismic, environmental and task constraints that ultimately dictates the optimal pattern of coordination and control for specific individuals, clearly some constraints will be more influential than others depending on the motor activity being performed and the specific requirements of the performance or rehabilitation context. To establish the relative impact of different constraints, an experimental research strategy is required that systematically manipulates to their extremes, either singularly or in combination, a broad range of organismic, environmental and task constraints, in a variety of different motor activities.[6,22,45] Such an approach is necessary because constraints on neurobiological systems are not always identifiable *a priori* nor are they particularly amenable to theoretical analysis. Furthermore, it is important to manipulate constraints through their entire range because small-scale changes in a particular constraint can lead to large-scale changes in patterns of coordination and control.[74]

Once constraint manipulations have been undertaken, it is necessary to monitor qualitative and quantitative changes in patterns of coordination and control. McGinnis and Newell[75] outlined a framework based on topological dynamics that uses biomechanical measurements – normally, but not limited to, kinematic time series data[47] – and control spaces for mapping movement to constraints. Each control space frame of reference (i.e. configuration space, event space, state space and state-time space) describes different spatio-temporal properties of movement and provides a useful insight into the restrictive nature of the constraints impinging on the system. The value of this topological approach is that it describes both movement and the imposing constraints in common terms – an issue that has been longstanding in the motor learning and control literature.[74] This framework also provides yet another opportunity for biomechanists and motor control to integrate their respective skills in genuine interdisciplinary collaborations (see Davids et al.[76] and Glazier et al.[77,78] for similar recommendations).

4. Conclusions and Implications for Sports Medicine

In this article, we have discussed the relative merits of simple and complex mathematical models of the neuromusculoskeletal system using pertinent examples from the literature. We have suggested that complex mathematical models might be considered superior to simple mathematical models since they enable basic mechanical insights to be made *and* individual-specific optimal movement solutions to be identified. However, to identify a complete optimal movement solution for any given motor skill, at any given instant in time, it is necessary to incorporate more of the essential constraints that collectively shape and guide the neuromusculoskeletal system through its preferred states of coordination and control. Some constraints are clearly more influential than others so a priority for biomechanists and motor control experts is to identify a hierarchy of nested constraints through the implementation of systematic experimental research programmes. Although the computer technology and methodological procedures are currently not available to implement such a framework, we believe that the constraints model offered by Newell[6] could, in principle, be used by sport and exercise biomechanists working towards the complete optimization of human movement. Adopting such a model of human movement organization involves re-conceptualizing the human neuromusculoskeletal system, not as a linear, deterministic, mechanical system, but rather as a non-linear, stochastic, biological system.

The notion of individualized adaptation to specific constraints has major implications for scientists working in the related fields of ergonomics, robotics, cybernetics, and more pertinently to the field of sports medicine. Traditionally, practitioners in sports medicine, rehabilitation and therapy have been strongly influenced by the 'medical model', in which variations in movement patterns are often viewed as deviations from a hypothetical 'norm' rather than as adaptive behaviours on the part of individuals who are seeking to satisfy the unique range of interacting constraints on them.[79] Viewing physical, perceptual or cognitive differences in a positive or negative light is too judgmental of individual variations in movement solutions. From this viewpoint, a physical, perceptual or cognitive disability should be viewed as a constraint on the structure or function of the individual neuromusculoskeletal system. Indeed, the use of the term 'disability' to refer to an individual's personal constraint, such as a lower-limb amputation, implies a value judgement on the part of the observer, and in the constraints-led approach there are no negative connotations attached to this system state. Unique structural or functional constraints merely describe different states of neurobiological system organization and would be likely to add to the existing variations observed in the diversity of human behaviour.

For example, the misconception of 'common optimal movement patterns' exists in the study of human movement behaviour and has infiltrated the study of neuro-perceptual-motor disorders. Many clinicians have derived a unitary, biologically determined perspective of health and movement behaviour in which variability is viewed as deviation from 'accepted' norms. In medicine, individual variability is often seen as dysfunctional and an index of abnormality. In this traditional medical model, health and performance behaviours are identified as 'problems' for the individual if they deviate from what are perceived as accepted population norms. The idea that current clinical and medical practice does not recognize individual variation enough has begun to emerge in science. For example, West[80] proposed that science and medicine has tended to overemphasize the significance of an average value in observations of phenomena related to individual health. The science of complexity has questioned traditional assumptions in physiology, supported by innovative thinking in fractal physiology, which pre-supposes that understanding variability provides more insights into an individual's health than does measuring average values in system behavior. According to West,[80] it is important to understand that variability in system behaviours such as heart rate, breathing and walking are much more susceptible to the early influence of disease than are averages. The over-use of central tendency and dispersion statistics in medicine has been implicated in this perspective.[80]

An alternative view prompted by dynamical systems theory is that variability in movement behaviour may be viewed as individual adaptations to unique structural or functional constraints. Variability has a functional role in helping individuals adapt to ever-changing constraints imposed on them by environmental, anatomical and physiological changes due to performance, disease, injury and aging.[81] An implication of this view for sports clinicians is that movement behaviours exist on a spectrum characterizing the boundaries of naturally occurring variability. From this standpoint, the terms 'impaired' and 'elite', used in relation to performance in sport and exercise, need to be understood as relative and interpreted in relation to the constraints on each individual because the precise location of a neuromusculoskeletal system in the performance spectrum emerges from the multitude of constraints acting upon it at specific points during the lifespan. Since the constraints on each individual are many and unique, it follows that movement solutions will differ within and between individuals in order to optimize functionality. As Latash and Anson[82] noted, the "phenomena of variability of voluntary movements by themselves indicate that 'correct' peripheral motor patterns may form a rather wide spectrum". This fundamental insight applies to healthy individuals across the lifespan as well as those with injuries, diseases and perceptual-motor disorders. In line with the arguments of Latash and Anson,[82] it is clear that adaptations to constraints should not necessarily be perceived as pathological since motor patterns may be optimal for the conditions affecting an individual's motor system at any point in time. Motor patterns in individuals with cognitive, perceptual and motor deficits have been labelled by some sports clinicians as 'abnormal' compared with 'common optimal motor patterns' idealized in a 'medical model' approach. However, we have argued that they may be better viewed as a functional and emergent response under the confluence of constraints that each individual needs to satisfy in different performance environments. Therefore, treatment interventions in sports medicine should not be directed towards the achievement and maintenance of an 'ideal' motor pattern during therapy or rehabilitation (a sort of 'one-size-fits-all' approach). The overarching aim of sports clinicians should be to help individuals satisfy the multitude of unique constraints acting on them, improving their functionality in the performance environment.

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