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Towards a More Balanced Understanding of Motor Control Systems

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Abstract

Roberts's book provides a reasonably thorough guide to the physiology and biomechanics of balance, unfortunately the discussion of the neural and cognitive aspects of motor control is less satisfactory. We propose that Roberts's statement of the problem of balance control should be extended to include control of non-equilibrium states, and we discuss sensorimotor calibration and integration in the context of maturation of the organism.

Commentary on: Roberts, Tristan D. M. (1996) Understanding Balance:The Mechanics of Posture and Locomotion, Psycoloquy: 7,#2 Posture Locomotion (1)

Keywords: balance, cognition, information processing, locomotion, model, motor control systems, Parkinsonism

1. Roberts is to be congratulated on providing a useful and informative guide to the basic anatomy and physiology of the control of posture and balance, and a clear exposition of the biomechanics of balance and gait. Unfortunately his book is less satisfactory in its treatment of the general principles by which the nervous systems of mammals enable them to move around effectively in a complex environment, and in particular of the description of the cognitive and neural mechanisms of movement. Roberts proposes that posture and locomotion are controlled by a combination of "central" processes which rely on autonomous central mechanisms and more "peripheral" processes which rely on sensory information. He describes the framework within which the central processes act by discussing balance behaviour in terms of "the appropriate organisation of the forces developed between the body and its supports". The peripheral processes are said to be concerned with sensory stimulation, and he makes much of the difficulty involved in relating neural signals to both the physical variables and the states of affairs requiring action. His solution to this problem uses the terminology of gestalt recognition and proposes

that modern connectionist models can account for the recognition of "relevant stimuli" by the nervous system. This solution, however, seems strongly reminiscent of F. Rosenblatt's theory of brain mechanisms of the early 1960's long before the paradigm of connectionism.

2. Although the first chapter of the book is entitled "The Problem" a clear statement of the problem of balance is missing, in particular the chapter appears to concentrate mainly on balance as the maintenance of equilibrium. In common usage we speak of someone losing or maintaining balance in situations where they are manifestly not in equilibrium, rising from a chair or when walking on a moving vehicle for example. It is the problem of maintaining control of posture under these circumstances which requires a clear definition, controlling static equilibrium is a subset of this more complex activity.

3. We propose the following definition:

Control of posture and locomotion involves regulation of the positions and motions of the various parts of the body in relation to each other and to one or more external reference frames in order to achieve the organism's goals.

The crucial points in this definition are, firstly, that it involves control of motion as well as control of position, and, secondly, that there may be more than one frame of reference relevant to control of balance. Control of motion, particularly of the momentum of the various segments of the body, is of the greatest importance. Loss of control of momentum and the absorption of the associated kinetic energy by body structures during a collision can result in broken bones or damage to soft tissue structures. Also, Roberts reminds us that proper control of momentum transfer between body segments is essential for energy efficient gait, and in fact for efficient performance of many motor tasks. The normal context for control of balance is provided by gravity and the local configuration of the environment (flat ground, rocks, trees, stairs, etc.). However, a leopard pursuing an antelope or a man running for a moving bus must not only control their motion in relation to this normal reference frame, but also in relation to a second frame which will in general be moving in a complex way. Arriving on the moving object with incorrectly judged momentum is in either case likely to lead to disaster. The regulation of posture is always directed towards the achievement of some goal or goals of the organism, and while, we agree with Roberts that it is not appropriate here to consider questions of conscious experience, it is nevertheless important to remember that changes in goals produce changes in expectation (or "postural set") which can make the organism respond differently to identical stimuli presented on different occasions. The interaction between perception and action can thus be studied on various levels, beginning with analysis of biomechanical and electrophysiological problems and ending finally with philosophical discussions about consciousness.

4. The bodies of mammals are complex assemblies which require continuous active control, even when the organism is standing still. Control requires information on the relative motions of body parts (interoception) and motion in relation to the environment (exteroception). The complexities of the various sensory systems and their non-linearity and the uncertain relationship of their output to the physical variables of mechanics are covered in detail in the book. Control also requires generation of

forces with the appropriate time varying direction and magnitude, and Roberts discusses muscle physiology and mechanics at some length but a general solution of the control problem needs to address the following points which he does not cover adequately.

5. Control of balance requires accurate characterisation of the motion of the body and the production of motor commands with the appropriate spatial and temporal organisation. The time available for this is constrained by physical factors and ranges from tens to hundreds of milliseconds, slower responses will in general fail to provide effective control. Systems controlling balance must cope not only with the large number of degrees of freedom of the body and the vagaries in performance of its sensors and effectors, but also with change in their characteristics over time. As the organism proceeds from birth to death its physical configuration changes considerably, size, weight and therefore inertia increasing as the organism grows. In the short term fatigue, and in the long term disease, injury and ageing affect the performance of all parts of the system.

6. We argue that an understanding of the ways in which the organism deals with the necessity to adapt to change is essential to an understanding of control of balance, because when we examine the motor skills of an organism we are observing the outcome of a long process of sensorimotor integration. The most important and complex part of this process occurs in the period of maturation which follows birth as the organism calibrates its sensory, nervous and muscular systems. Some degree of control is already present at birth, the amount varying between species. The young of some species must be able to stand and walk very soon after birth, these are quadrupedal creatures whose stance and walking gait (given functional weight bearing reflexes) are inherently stable at all times (chapter 7). In man, apes and monkeys, infants begin with a quadruped gait (crawling) and progress only slowly to bipedal standing and walking. The neural circuitry for control of weight bearing and stepping is present in newborn human infants, but the corresponding motor activity can only be observed under special circumstances (chapter 6).

7. Roberts argues that the constellation of neural signals from a particular sensor (muscle spindle or semicircular canal for example) contains no exact representation of the variables which engineers would use when implementing a control system, and he argues further that reconstruction of these variables, if it is possible at all, is a very complex task. Even more complex transformations are required to produce motor command signals from these inputs. The sensory and motor systems do require calibration, but this calibration is implicit rather than explicit, that is, the exact details of the relationship between external variables and their internal representation by neural signals is specific to the individual organism. This is also true of the signals in the structures which generate motor commands in response to sensory cues, they have "meaning" for the organism only insofar as they carry out their intended function. These signals may more or less resemble one another in individuals of the same species, but they are very unlikely to be identical. Roberts discusses connectionism and the tuning of neural networks briefly, and we believe that this process is the clue to understanding the way in which sensorimotor calibration is accomplished. The relationships between incoming sensory information and appropriate motor responses are instantiated in the interconnections and behavioural properties of the neurons involved, and are built up and tuned by the organism as it matures, and also as it learns a new skill when mature. Much of this is mentioned in the book, but the discussion is insufficiently detailed

and lacks organisation.

8. Certainly, as Roberts suggests, any model of motor control has to be concerned with multiple simultaneous inputs and outputs. However, his general principle of a distinction between reflexes and habits seems to introduce the sort of metaphor that has subverted the psychological study of learning throughout this century. At least since the publication of Miller, Galanter and Pribram's seminal text "Plans and structure of behaviour" this distinction has been seen to be without explanatory utility. It has been widely acknowledged that central and/or peripheral oscillators, central motor programs, coordinative structures and strategic motor sets all contribute to the control of balance and locomotion, but all these processes are more or less disqualified by Roberts. Although these concepts are often seen as mutually exclusive, it is our view that they can be thought of as different approaches to the problem of motor control, emphasising different mechanisms. Motor synergies are spatially and temporally organised activity patterns in groups of muscles appropriate to a particular task, which occur not only in response to disturbance of ongoing motor acts, but also as anticipatory activity which prepares the organism for the consequences of forthcoming voluntary motor activity. Grouping of this kind is one method of dealing with the multiple degree of freedom problem discussed by Bernstein, and there is an extensive literature on this topic which Roberts does not discuss. Instead he seems to confine his discussion to the model of gestalt recognition, without specifying the gestalt components of proprioceptive stimulation or the "adequate stimulus situation" for activities other than hopping. Although his general statements often seem plausible, his account of motor control fails to provide sufficient specific information for the formulation of testable hypotheses. This lack of detail is especially obvious in the last chapter of the book about central processing, which is more in the nature of a broad brush list of empirical findings and problems than a description of a structured framework for the understanding of movement control.

9. Roberts's account of the basal ganglia diseases, in particular Parkinson's Disease (PD), seems a typical example of his rather sketchy account of the mechanisms of motor control, in this case movement disorders. His emphasis on the role of L-Dopa seems rather more informed by Oliver Sacks "Awakening" story, which of course is a fascinating description of the early situation, than by recent research about the motor behaviour of PD patients. Parkinsonism is normally characterised by poverty of movement (hypokinesia) and resistance to stretch (rigidity), and secondarily by tremor at rest. The most consistent lesion seems to be a degeneration of dopaminergic (DA) neurons in the substantia nigra pars compacta and its terminating axons in the striatum as described by Roberts. However, the pathological changes in Parkinsonism are not restricted to DA paths in the dorsal basal ganglia nor to the characteristic dyskinesias. In recent years increasing effort has been concentrated on the role of the basal ganglia and their cortical connections in cognition in order to understand specific clinical features of parkinsonism. Despite extreme motor difficulties, one often finds very little or no difficulty exists in perception, learning, thinking, or intellectual aspects of speech. As Marsden has rightly pointed out patients with Parkinson's disease suffer no general loss of cognitive functions but there are conditions under which specific functions (e.g., visuospatial, recall, attention, spatial memory) are impaired. Also, the poverty of movement includes deficiencies in the automatic coordination of high-level motor plans, such as the greatly diminished ability to perform more than one motor task at the same time or to concentrate sufficiently in order to combine successive motor acts. In this respect Roberts's attempt to

emphasise the importance for movement control of integrating various information processes seems important. Surely the influence of the integration of sensory processes and its relation with high-order cognition in control of body movements has been grossly underestimated, but Roberts's attempt to model these integrative processes by suggesting parallels (e.g., illusionary contours) with the processes involved in visual gestalt perception seems highly speculative. In Roberts's hands the concept of gestalt recognition becomes an all embracing label which covers not only the integrative aspect of motor control, but also the whole area of visual perception and speech perception and even the concept of "the self" and "conscious experience" in general. In this respect his proposed framework for studying posture and balance, whose production appears to have been precipitated by the failure of any theory so far to provide a unified conceptual description of locomotion and balance, is rather empty because it tries to explain too much. We ask ourselves whether this failure might be a consequence of the way in which the problem of movement control has been defined so far. Thus, we suggest that the study of motor disorders would be most useful if focused on specific motor tasks and clearly isolated clinical features instead of formulating generalisations about functional deficits common to the PD population.

10. Finally, the discussion of the cognitive elements of the motor control system and the mechanisms of control is relatively unsophisticated. One reason for this seems to be that the actual environmental demands and motor tasks in which the organism engages are not sufficiently differentiated, and in addition to the physical demands, at least three cognitive factors are likely to influence the control of movement: the demands of the task, motor sets, and stimulus/motor strategies. Furthermore, Roberts does not entertain the positions that our own actions are relatively inaccessible to perceptual/cognitive judgement, and that the distinction between "sensory" and "central" driven processes is a rather nebulous concept. Would the adoption of such views contribute to a better understanding of why thinking about "where to place the feet whilst running upstairs" generally leads to a trip or stumble?

11. To summarise, Roberts's text provides an excellent example of what a mainly physiological and biomechanical account of balance control systems might look like and what problems it is confronted with. It demonstrates clearly which aspects a cognitive account of movement control might usefully address, and what constraints such an account would face. However, his claim to have formulated general rules for processing sensory information and for parameterisation of motor programs is insufficiently detailed and unsupported by a reference list of the existing literature. Unfortunately, a missing reference section may prevent the use of his book as a proper textbook, but the reader might find the book useful as a quick guide.

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