J Neurol (2003) 250 : 257–258

Motor co-ordination in humans is guided by optimal feedback control

In the 1940s, Norbert Wiener and his colleagues at the Massachusetts Institute of Technology and Harvard University School of Medicine formulated the theory of cybernetics – the art of steering – in order explain various aspects of complex behaviour observed in man and the machine. One of the crucial factors of this theory involves feedback control, i. e. the partial return of information on a system's output in order to allow self-corrective action. This concept has proven to be fruitful in explaining motor control functions in humans and higher animals, and in designing machines to perform complex tasks, such as robots. The emergence of the digital computer, the widespread acceptance of behaviourism, and the assumption that human information processing systems operate serially, give the impression that feedback control mechanisms must lead to stereotypical behaviour. Our fascination with the design of human-like robots which can perform extremely complex tasks without fatigue, has necessarily increased the belief that the behaviour of humans must be, or rather should be, governed by some kind of stereotypical, albeit inadequate, pattern, and that feedback mechanisms play a key role in this model. In other words, in humans, as in robots, there is a separation between trajectory planning (intention) and trajectory execution (body movement) for the completion of a complex task, and that any existing redundancies, or task-irrelevant dimensions, are eliminated prior to executing the desired trajectory. Computational efficiency is the dominant principle.

However, such models ignore the evolution of humans and higher animals, i. e. the information-processing constraints imposed by their biological and computational capacities, which have, nevertheless, given them the ability to move their bodies rapidly and elegantly, as compared to the precise – but wooden – movements of a robot. This apparent inadequacy of humans paradoxically reveals a superior strategy for executing highly controlled motor behaviour. We possess more degrees of freedom than are needed to perform a defined task, but are required to co-ordinate them in order to reliably accomplish high-level goals, while faced with intense motor variability. In an attempt to explain how this takes place, Emanuel Todorov and Michael Jordan [1] of the Department of Cognitive Science, University of California, San Diego and the Division of Computer Science and Department of Statistics, University of California, Berkeley, have formulated an alternative theory of human motor co-ordination based on the concept of stochastic optimal feedback control. The theory, and the data of supporting experiments, were recently published in the November 2002 issue of Nature Neuroscience. In this way, the authors are able to conciliate the requirement of goal achievement (e. g. grasping an object) with that of motor variability (biomechanical degrees of freedom). Moreover, the theory accommodates the idea that the human motor control mechanism uses internal 'functional synergies' to regulate task-irrelevant (redundant) movement. Todorov and Jordan point out that humans actually employ feedback control mechanisms more intelligently than was assumed in the past, and that the optimal strategy taken when confronted with uncertainty is to correct irrelevant deviations which interfere with goal achievement. This means that motor variability is constrained, but not completely suppressed, when carrying out a particular task. In other words, a desired trajectory is not forced, but open for eventual alterations, which may be required in the final moment before a task is performed.

The authors postulate that the human motor system estimates the best possible control scheme or law in order to perform an assignment. The feedback control law determines immediately occurring redundancies by using all available information in order choose the best course of action (dynamic systems model), thereby making no difference between trajectory planning and execution – as opposed to mechanisms involved in stereotypic behaviour. The alternative theory of human motor co-ordination formulated by Todorov and Jordan is also based on the general observation that fast movements are less accurate because the motor system's noise (signal disturbance) increases proportionately. The authors point out that multiplicative noise has been used extensively in feedback control models in engineering, however in their model of human motor co-ordination, the magnitude of sensory and motor noise is determined in order to describe how the optimal control law can match the variability expressed by experimental data.

Todorov and Jordan support their alternative theory by requiring human subjects to perform a series of motor tasks, such as in the pistol shooting task, where subjects were required to move an LED pointer (hand-held laser pistol) through sequences of circular targets projected on a table. The subject moves the pointer from the starting target to the other targets displayed on the table. In another motor task, subjects were required to form a ball out of a square sheet of paper (20 × 20 cm) as quickly as possible. Subjects also performed hitting and throwing tasks with ping-pong balls to a target. The data generated by these experiments were subsequently analysed using numerical simulations within a linear-quadratic-Gaussian (LQG) framework, which was adapted in order to be subject to multiplicative noise. The LQG framework has been used previously in various motor control studies. For more information on the methodology, refer to the Supplementary Notes available on the Nature Neuroscience website.

The authors point out that their experimental data support the assumption that optimal performance in a behavioural task is actually achieved by the use of redundancy. This is why constrained variability has been observed in various unrelated behaviours. The operation of task-optimal control laws, rather then computational short cuts, appear to underlie observations such as task-constrained variability, goal-directed corrections, motor synergies and controlled parameters. Redundancy is not a problem, but rather a crucial aspect of performing the task. Thus, task-irrelevant deviations in behaviour are only corrected when they interfere with goal achievement (minimal intervention principle). The increase in deviations from the trajectory is tolerated economically in order to preserve control space dimensions (motor synergies).This means that an unnecessary corrective signal would actually be detrimental to task performance because – as Todorov and Jordan stress – both noise and effort are control dependent and would increase. Motor variability may therefore lie at the heart of systems identification (feedback), and support the concept of optimal feed back control. The authors also note that in the performance of a particular task, the underlying optimality principle (explanation of system behaviour and specification of control law) remains the same, but not the so-called feedback controller. The feedback controller is unique for a particular task, and can only be revealed within the context of that task. For this reason, it needs to be studied in a wide range of behaviours in order to better understand the underlying sensorimotor loops. This will be the subject of future research.

In his commentary on the Todorov and Jordan study, Stephen H. Scott [2] of the Department of Anatomy and Cell Biology, Centre for Neuroscience Studies, Queen's University, Ontario, Canada, notes that this investigation provides a framework for explaining how motor co-ordination in humans and higher animals allows them to perform highly complicated movements elegantly, despite variability. The study also gives insight as to how optimal feedback control functions produce co-ordinated behaviour, nevertheless this model of motor control brings with it a high computational price. The theory illustrates that mathematical tools are lacking which describe feedback control in the motor systems of higher animals. Scott criticises the optimal control theory of Todorov and Jordan, because it ignores the fact that neural circuits controlling movement are widely distributed and complex. Thus, as he concludes, certain features of a particular motor circuit may only be optimal when considering the complete behavioural repertoire present in both humans and animals.

References

1. Todorov E, Jordan MI (2002) Optimal feedback control as a theory of motor coordination. Nature Neuroscience 5: 1226–1235
2. Scott SH (2002) Optimal strategies for movement: success with variability. Nature Neuroscience 5:1110–1111

Dr. rer. nat. Clay E. Reilly
Gstaltenrainweg 73
4125 Riehen, Switzerland
E-Mail: cer@datanetworks.ch