



The problem of measurement indeterminacy in complex neurobiological movement systems

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ABSTRACT

In the study of complex neurobiological movement systems, measurement indeterminacy has typically been overcome by imposing artificial modelling constraints to reduce the number of unknowns (e.g., reducing all muscle, bone and ligament forces crossing a joint to a single vector). However, this approach prevents human movement scientists from investigating more fully the role, functionality and ubiquity of coordinative structures or functional motor synergies. Advancements in measurement methods and analysis techniques are required if the contribution of individual component parts or degrees of freedom of these task-specific structural units is to be established, thereby effectively solving the indeterminacy problem by reducing the number of unknowns. A further benefit of establishing more of the unknowns is that human movement scientists will be able to gain greater insight into ubiquitous processes of physical self-organising that underpin the formation of coordinative structures and the confluence of organismic, environmental and task constraints that determine the exact morphology of these special-purpose devices.

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1. Introduction

Indeterminacy in complex neurobiological movement systems has been a perennial problem – a “nightmare” as Winter (1989, p. 338) described it – for human movement scientists attempting to study the causative mechanisms underlying normal and pathological human motor functioning. In mathematical parlance, indeterminacy is where there are more unknowns than there are independent equations that define the system (Vaughan, 1996). Indeterminacy is closely related to redundancy, which is where there are more individual component parts or degrees of freedom than are strictly necessary to perform a given task successfully (Bernstein, 1967). Although the two terms have often been used interchangeably (e.g., Bartlett, 1999), it could be argued that they are, in fact, different because, in principle, indeterminacy can be solved by identifying and quantifying the unknowns or overcome by imposing artificial modelling constraints to reduce the number of unknowns, whereas a redundant system will always be redundant because no degrees of freedom are ever removed or eliminated unless through surgical intervention (Latash, 2000).

Gelfand and Latash (1998) argued that since all degrees of freedom contribute to the fluid production of bespoke movement solutions and the attainment of task goals, the term redundancy

is, in fact, a misnomer and should be abandoned in favour of the principle of abundance. Latash (2000) even suggested that much of the confusion regarding the terms redundancy and abundance was because the Russian word *izbytochnost* used in Bernstein's original writings can mean either depending on context. Similarly, Tononi et al. (1999) and Edelman and Gally (2001) suggested that the term degeneracy was more appropriate than redundancy in neurobiological movement systems. They argued that redundancy should be reserved for electronic or mechanical systems where duplication or repetition of *identical* system components is an important design feature that provides back-up in case of system failure. However, in neurobiological movement systems, degeneracy is a more suitable descriptor as system components that are structurally *different* are still able to perform the *same* or *different* function or produce the *same* or *different* output depending on the context in which they are expressed (see Fig. 1 of Edelman and Gally (2001) for examples of degeneracy at different levels of neurobiological system organisation). Therefore, inherent neurobiological flexibility in achieving performance outcomes is not just a feature of the *number* of available motor system degrees of freedom (captured by system redundancy) but also the *role* of these micro-components in assembling actions (captured by degeneracy).

In this paper, we examine the problem of measurement indeterminacy for human movement scientists and how it relates to the study of complex neurobiological movement systems. It will become apparent that the primary cause of this

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indeterminacy is the inadequacy of contemporary measurement methods, such as inverse dynamics and electromyographic analyses, currently being used by human movement scientists. We explore strategies used to overcome the indeterminacy caused by these methodological deficiencies and discuss why these approaches prevent human movement scientists from gaining a more complete understanding of what Turvey (1990, p. 940) described as the "... most primitive independently governable actuators of movement"—the coordinative structure or functional motor synergy (referred to henceforth simply as coordinative structures). We begin, however, by briefly introducing this seminal theoretical concept and its role in the functioning of neurobiological movement systems.

2. The definition and role of coordinative structures in complex neurobiological movement systems

Kugler et al. (1980, p. 17) originally defined a coordinative structure as "... a group of muscles often spanning several joints that is constrained to act as a single functional unit". Subsequently, Kay (1988, p. 344) defined them, more generally, as "... an assemblage of many micro-components ... assembled temporarily and flexibly, so that a single micro-component may participate in many different coordinative structures on different occasions", better reflecting the universality of this concept at different levels of analysis and more effectively capturing the degenerate nature of neurobiological movement systems. The specific morphology of coordinative structures is entirely dependent on the internal and external constraints acting on the neurobiological movement system and ubiquitous processes of physical self-organisation (e.g., Kugler et al., 1980; Newell, 1986; Kelso, 1995). A distinguishing feature of these task-specific structural units is that if one of the constituent parts introduces an error into the common output, the other constituent parts automatically make compensatory adjustments to minimise the effect of the original error (Latash et al., 2002). As we elaborate on below, coordinative structures are strongly related to the phenomenon known as sensorimotor equivalence—that is, the attainment of a particular task goal by a seemingly infinite number of different motor patterns.

3. Evidence of coordinative structures in complex neurobiological movement systems

Coordinative structures have been identified at a number of levels of analysis in neurobiological movement systems. Some of the earliest evidence of their existence at the kinematic level of analysis was provided by Bernstein (1967) in a study of professional blacksmiths. He reported that the variability of individual joint trajectories over a series of hammer strikes was greater than the variability of the trajectory of the hammer head. However, rather than acting independently, Bernstein (1967) concluded that the joints of the arm acted in symbiosis to compensate for errors introduced at individual joints. Similar findings were reported by Arutyunyan et al. (1968) in an investigation of shooting at a target. They reported that experienced marksmen exhibited covariations in the position of their shoulder and wrist joints thereby minimising variability in the spatial orientation of the gun barrel. In contrast, inexperienced marksmen did not exhibit any compensatory movements and, therefore, displayed increased variability or error in the spatial orientation of the gun barrel and greater dispersion of shot outcomes.

At the kinetic level of analysis, Winter (1984) provided evidence of coordinative structures during the support phase of gait. He found that, in the presence of fairly stable joint trajectories, there was significant within-subject variability in net joint torques at the knee and, more markedly, at the hip. However, far from being random, this variability was interpreted as being compensatory as the net joint torques at the hip and knee were allowed to covary, enabling the net extensor pattern or total support moment (the algebraic sum of the net joint torques at the hip, knee and ankle) to be maintained, thus preventing the stance leg from collapsing. Winter (1984) reasoned that covariations between the hip and knee joints enabled the neurobiological movement system to produce consistent joint trajectories even if erroneous net joint torques were introduced at individual joints.

Finally, several studies have suggested that coordinative structures may exist at the neurologic level of analysis. Hatze (1976) compared muscle activation patterns of measured (near optimal) and simulated (optimal) limb movements during the performance of a kicking action. He found that, despite the production of almost identical kinematic profiles, the measured and simulated limb movements produced substantially different muscle activation patterns. In a more recent computer simulation, Hatze (2000) showed that comparatively chaotic neural control inputs were still able to produce highly coordinated movement patterns. Similarly, it was shown that individual muscle moments could be perturbed to a considerable extent without significantly affecting the observable motion of the body segments.

4. The problem of measurement indeterminacy needs to be solved not overcome

Empirical and theoretical evidence outlined above clearly demonstrates that coordinative structures exist at different levels of complex neurobiological movement systems and that they afford considerable flexibility and adaptability in achieving task goals. However, the problem of indeterminacy arises because current biomechanical measurement methods, such as inverse dynamics and electromyographic analyses, are incapable of measuring, with any degree of precision, the output of individual elements comprising these coordinative structures and, therefore, their contribution to the output of these task-specific units cannot reliably be determined.

Although a number of studies have attempted to establish more of the unknowns by combining various measurement methods (e.g., electromyography, kinematics, external force measurements) or by static and dynamic optimisation procedures where specific physiologic or energetic cost functions have been minimised (e.g., Glitsch and Baumann, 1997; Anderson and Pandey, 2001), the problem of measurement indeterminacy has traditionally been overcome in biomechanical studies by imposing artificial modelling constraints to reduce the number of unknowns. For example, during inverse dynamics analyses, all muscle, bone and ligament forces crossing a joint have typically been reduced to a single vector—that is, the net or resultant joint torque (Vaughan, 1996). However, this approach does not provide any information about the contribution of agonist and antagonist muscle action around a particular joint nor can it allow the contribution of an individual muscle within a particular group of muscles to be verified.

Clearly, if a greater insight into coordinative structures is to be gained, biomechanists must *solve* the problem of measurement indeterminacy by identifying and establishing more of the unknowns rather than just *overcoming* it by imposing artificial constraints to reduce the number of unknowns. By determining more of the unknowns, human movement scientists would be

able to investigate, and gain a better understanding of, the ubiquitous processes of physical self-organisation that underpin the formation of coordinative structures and the confluence of organismic, environmental and task constraints that determine the exact morphology of these task-specific units (e.g., Kugler et al., 1980; Newell, 1986; Kelso, 1995). As neurobiological movement systems are inherently stochastic (Riley and Turvey, 2002), it is likely that the specific contribution of individual elements of coordinative structures over iterative performances of the same motor skill will range from being random to largely deterministic. In addition to advancements of methodological procedures, the application of analytical tools of non-linear dynamics, such as principal component analysis (e.g., Daffertshofer et al., 2004) and approximate entropy (e.g., Stergiou et al., 2004), might also be useful in establishing invariant and variant features of these special-purpose devices.

5. Conclusion

Coordinative structures are a central feature of skilled movement. Evidence of their existence has been documented in the literature but further research is required to establish their role, functionality and ubiquity at different levels of complex neurobiological movement systems. To gain a better understanding of these important task-specific structural units, human movement scientists must work towards solving the problem of indeterminacy that they pose rather than overcoming it by imposing artificial modelling constraints. Current measurement methods must, therefore, improve so that more of the unknowns can be identified and quantified.

Conflict of interest statement

The authors have no conflicts of interest directly relevant to the contents of the submitted manuscript.

References

Anderson, F.C., Pandy, M.G., 2001. Dynamic optimization of human walking. *Journal of Biomechanical Engineering* 123, 381–390.

- Arutyunyan, G.H., Gurfinkel, V.S., Mirsky, M.L., 1968. Investigation of aiming at a target. *Biophysics* 13, 536–538.
- Bartlett, R.M., 1999. *Sports Biomechanics: Reducing Injury and Improving Performance*. E&FN Spon, London.
- Bernstein, N.A., 1967. *The Coordination and Regulation of Movements*. Pergamon Press, Oxford.
- Daffertshofer, A., Lamoth, C.J.C., Meijer, O.G., Beek, P.J., 2004. PCA in studying coordination and variability: a tutorial. *Clinical Biomechanics* 19, 415–428.
- Edelman, G.M., Gally, J.A., 2001. Degeneracy and complexity in biological systems. *Proceedings of the National Academy of Sciences of the United States of America* 98, 13763–13768.
- Gelfand, I.M., Latash, M.L., 1998. On the problem of adequate language in motor control. *Motor Control* 2, 306–313.
- Glitsch, U., Baumann, W., 1997. The three-dimensional determination of internal loads in the lower extremity. *Journal of Biomechanics* 30, 1123–1131.
- Hatze, H., 1976. The complete optimization of a human motion. *Mathematical Biosciences* 28, 99–135.
- Hatze, H., 2000. The inverse dynamics problem of neuromuscular control. *Biological Cybernetics* 82, 133–141.
- Kay, B.A., 1988. The dimensionality of movement trajectories and the degrees of freedom problem: a tutorial. *Human Movement Science* 7, 343–364.
- Kelso, J.A.S., 1995. *Dynamic Patterns: The Self-Organization of Brain and Behavior*. MIT Press, Cambridge.
- Kugler, P.N., Kelso, J.A.S., Turvey, M.T., 1980. On the concept of coordinative structures as dissipative structures: I. Theoretical lines of convergence. In: Stelmach, G.E., Requin, J. (Eds.), *Tutorials in Motor Behavior*. North-Holland, Amsterdam, pp. 3–47.
- Latash, M.L., 2000. There is no motor redundancy in human movements. There is motor abundance. *Motor Control* 4, 259–261.
- Latash, M.L., Scholz, J.P., Schöner, G., 2002. Motor control strategies revealed in the structure of motor variability. *Exercise and Sport Sciences Reviews* 30, 26–31.
- Newell, K.M., 1986. Constraints on the development of coordination. In: Wade, M.G., Whiting, H.T.A. (Eds.), *Motor Development in Children: Aspects of Coordination and Control*. Martinus Nijhoff, Dordrecht, pp. 341–360.
- Riley, M.A., Turvey, M.T., 2002. Variability and determinism in motor behavior. *Journal of Motor Behavior* 34, 99–125.
- Stergiou, N., Buzzi, U.H., Kurz, M.J., Heidel, J., 2004. Nonlinear tools in human movement. In: Stergiou, N. (Ed.), *Innovative Analyses of Human Movement: Analytical Tools for Human Movement Research*. Human Kinetics, Champaign, IL, pp. 63–90.
- Tononi, G., Sporns, O., Edelman, G.M., 1999. Measures of degeneracy and redundancy in biological networks. *Proceedings of the National Academy of Sciences of the United States of America* 96, 3257–3262.
- Turvey, M.T., 1990. Coordination. *American Psychologist* 45, 938–953.
- Vaughan, C.L., 1996. Are joint torques the Holy Grail of human gait analysis? *Human Movement Science* 15, 423–443.
- Winter, D.A., 1984. Kinematic and kinetic patterns in human gait: variability and compensating effects. *Human Movement Science* 3, 51–76.
- Winter, D.A., 1989. Biomechanics of normal and pathological gait: implications for understanding human locomotion control. *Journal of Motor Behavior* 21, 337–355.