Ludovic SEIFERT

Motor coordination and expertise

A complex system approach of motor control in physical and sports activities

LAP LAMBERT Academic Publishing

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Impressum/Imprint (nur für Deutschland/ only for Germany)
Bibliografische Information der Deutschen Nationalbibliothek: Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.d-nb.de abrufbar.

Coverbild: www.ingimage.com

Verlag: LAP LAMBERT Academic Publishing GmbH & Co. KG
Dudweiler Landstr. 99, 66123 Saarbrücken, Deutschland
Telefon +49 681 3720-310, Telefax +49 681 3720-3109
Email: info@lap-publishing.com

Herstellung in Deutschland:
Schaltungsdienst Lange o.H.G., Berlin
Books on Demand GmbH, Norderstedt
Reha GmbH, Saarbrücken
Amazon Distribution GmbH, Leipzig
ISBN: 978-3-8443-0875-4

Imprint (only for USA, GB)
Bibliographic information published by the Deutsche Nationalbibliothek: The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Cover image: www.ingimage.com

Publisher: LAP LAMBERT Academic Publishing GmbH & Co. KG
Dudweiler Landstr. 99, 66123 Saarbrücken, Germany
Phone +49 681 3720-310, Fax +49 681 3720-3109
Email: info@lap-publishing.com

Printed in the U.S.A.
Printed in the U.K. by (see last page)
ISBN: 978-3-8443-0875-4

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Printed by
Schaltungsdienst Lange o.H.G., Berlin

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Acknowledgments

We thank B. Bril, K. Davids, B. Bardy, C. Sève, D. Delignières, H. Toussaint, J.P. Vilas-Boas and D. Chollet for the interesting discussion and their review during the preparation of the manuscript.

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Introduction

In high-level sports, expertise means being capable of turning in the best performance possible. However, it is useful to distinguish between expertise as the culminating performance, result or product of an action, and expertise as the means or process leading to it. The distinction is useful because the learning curve for a skill is not always in phase with the performance curve (e.g., on a ski simulator, Nourrit et al., 2003).

According to the extensive works of Ericsson, expertise can be understood as a high level of performance that can be repeated over time. Ericsson and Lehmann (1996) defined an expert as an individual with at least ten years of deliberate, high-level practice. Two characteristics should be kept in mind: long practice and deliberate practice; that is, expertise results from repeated, motivated engagement that requires effort and concentration, both of which have little to do with talent (Ericsson & Lehmann, 1996). This conception of expertise as based on deliberate practice has been criticized with regard to the effects of age, sociocultural context, genetics, degree of specificity of the activity, motivation, and more broadly the implication of cognitive processes (Abernethy et al., 2003; Beek et al., 2003; Sternberg, 1996; Ward et al., 2004). Although expertise is reached only through conscious and continually renewed effort, the information processing and attentional processes of any voluntary act are not negligible and thus limit the cognitive processes (Abernethy et al., 2003). Referring to ecological and dynamical systems approaches to motor control, Beek et al. (2003) suggested that the nature of "subject-environment" or "perception-action" coupling is not the same for non-experts and experts, as the expert is more capable of exploiting information about task-related constraints in order to organize. Moreover, the cognitive perspective usually focuses on explicit learning to become expert and minimizes the benefits of incidental (i.e., by observation) (Bandura, 1971; Horn & Williams, 2004) and implicit (i.e., by exploration) learning (Masters, 2000; Masters & Maxwell, 2004). Explicit teaching means giving a series of verbal instructions on how to reach a goal; the learners translate these instructions into procedural knowledge that is stored in memory and mobilized as response algorithms, without taking into account their coupling with the environment or the functional role (i.e., adaptive) of variability (Davids et al., 2006). One criticism of explicit teaching is that, in fact, expertise and access to expertise are task-dependent, subject-dependent and environment-dependent (Newell, 1986; Davids et al., 2008).

Recognizing both the strengths and drawbacks of cognitive approaches, we present here a summary of our research using a complex system approach of motor control in order to analyze (i) expertise, not in terms of performance but rather as motor skill that results to expert performance, and (ii) the access to this expertise.

As we hold with a complex system approach of motor control, we will show how the biomechanical approach and dynamical systems theory are complementary and allow for a macroscopic analysis of motor behavior, notably through the study of motor coordination. Thus, we will show that motor coordination can be evaluated by a macroscopic and collective variable that captures the motor behavior, or its essential elements that interact and define "coordination." We first explain our choice of motor coordination, and the interacting elements that capture it, as the variable by which to analyze expertise.

The second fundamental question we address is whether there is an "expert" motor coordination mode that should be imitated. From the cognitive perspective of motor control, especially information processing theory (Schmidt, 1975, 1982), high-level expertise is the capacity to both reproduce the same behavior and increase the automatic part of the movement. If the central nervous system is assumed to be the organizer and prescriber of motor programs and action plans for the effector system, when the information entered into the motor program is identical from one trial to another, then the response should also be identical. In this framework, access to expertise occurs through a reduction in deviation by modifying the motor program entry parameters until expert behavior is achieved.

This cognitive approach of motor control and learning has found approval in the French national program for physical education and sport, notably in 1985, 1996 and today, with motor program parameters transformed into declarative and procedural knowledge and meta-knowledge that the student must appropriate in order to act. However, Bernstein (1967), Davids et al. (2008), Gibson (1966, 1979), Kelso (1984, 1995), Kugler and Turvey (1987), Turvey (1992, 2004, 2007), and Newell (1986, 1991) offered an alternative point of view that combined ecological approach with dynamical systems theory, providing a new epistemological framework for studying and understanding motor control and learning. Within this framework, there is no "ideal" motor coordination in the absolute sense but instead motor coordination that emerges from the interaction of constraints: task, environmental and organismic (Davids et al., 2004, 2008; Glazier & Davids, 2009; Newell, 1986). From this perspective, constraints are not in opposition to resources but give direction and restrain the range of possibilities. Expertise is thus the capacity to interact with constraints in order to exploit them to the fullest. In this sense, ecological and dynamical system approaches do not accord primacy to the central nervous system as the movement organizer and question the possibility of programming numerous degrees of freedom, i.e., the 800 muscles and 100 joints in the human body (Bernstein, 1967). In fact, human motor control may be part of a complex system in which different elements (musculoskeletal) at different levels (motor, neuronal, hormonal, etc.) interact temporarily in the organization of a response. The causality between perception and action is not linear, as assumed by cognitive scientists (identification of the sensory stimulus, selection and programming of the response by the central nervous system, motor response carried out by the peripheral effector system; Schmidt, 1975, 1982), but is somewhat circular (Kelso, 1995; Turvey, 2004, 2007): a "perception-action" coupling for the ecological theorists and "subject-environment" coupling for the dynamical systems theorists, for both of whom information is in the coupling that the subject constructs in interactions with the environment. In this framework, expertise is the continuous adaptation of coordination to a set of constraints rather than the imitation of a single "expert" coordination mode. Davids et al. (2004, 2008) recommended a "constraints-led approach" where in teachers manipulate the set of constraints that will help the desired behavior to emerge; that is, they use implicit teaching while respecting the individuality of each learner, rather than explicit teaching that enumerates a set of principles and rules for action that will allow the motor program parameters to be set (Masters, 2000, Masters & Maxwell, 2004).

The third issue dealt with here is the relationship between coordination, performance and efficiency. If we assume that the premises of dynamical systems theory are correct, especially that motor response emerges (and is not programmed) from the interaction of constraints (from task, environment and organism), the same performance should be reached by several routes. In other words, expertise is not exclusively defined by the capacity to reproduce but also by the capacity to adapt to constraints. Thus, differences in behavior for the same prescribed task at the same level of performance are not seen as deviations from expert performance, since the teaching approach does not lead the learner to imitation and reproduction. The approach encourages exploration, but this does not mean that the teacher or trainer cannot guide the learner. Also, in the study of relationships between "coordination" and "performance", we review the issue of variability and hypothesize that intra- and inter-individual variability are potential sources for individual adaptation to specific situations and not indications of error or deviance to be reduced (Bartlett et al., 2007; Davids et al., 2003; Hamill et al., 2000; Newell et al., 2006). This epistemological position underlines the uniqueness of each subject, who is far more than a computer, processing information. The statistical analyses are not based on sufficiently large numbers and group comparisons (i.e., means comparisons) with the goal of generalizing, but instead provide methods, for example, for determining coordination profiles and behavioral dynamics over time, and the classification of subjects and trials.

The study of the relationships between "coordination" and "efficiency" analyzes the cost of given coordination modes in order to determine the most efficient motor behavior at the lowest cost. This has been accomplished through the study of the relationships between motor coordination and energy cost, mechanical cost and efficiency indicators.

This book is presented in four parts:

(i) First, we present our ontological position that human motor control is a **complex system**, at the interface of biomechanics and motor control, and that dynamical systems theory provides insight into this complexity by moving beyond a purely mechanical and cognitive analysis of behavior.

(ii) The second part shows how the motor behavior could be analyzed as a complex and dynamic system: In this sense, complexity can only be analyzed by capturing it with an essential variable, termed collective or macroscopic.

(iii) The third part deals with the manipulation of constraints so that the expected behavior will emerge—what Davids et al. (2008) called the "constraints-led approach" that leads toward nonlinear teaching (Chow et al., 2006, 2007b; Davids, 2010).

(iv) Last, the relationship between coordination and performance (efficacy) or more broadly the problem of expertise is investigated, notably through the question of the intra- and inter-individual variability, which provides the opportunity to define coordination profiles. Our work suggests a model of expertise in the form of an hour glass. We have also investigated the efficiency (efficacy at the lowest cost, notably through the study of energy or mechanical cost) of behavior in order to link changes in motor coordination with propulsive efficiency when the task, environmental and organismic constraints are modified. We have also begun to explore the cost of various coordination modes (in agreement with the initial works in equine locomotion, Hoyt & Taylor, 1981; and those developed by Sparrow, 1983, 2000).

Part 1. Ontological position: from biomechanics to complexity science and dynamical systems theory—Toward a macroscopic view of motor control

This book would highlight how **dynamical systems theory** could be at the interface of biomechanics and motor control, in order to understand human motor behavior as a **complex system**. It is perhaps worth explaining how biomechanics and motor control are related through dynamical systems theory and more broadly through the sciences of complexity.

1. Biomechanical approach to motor behavior: The current status and critical analysis

Hay (1980, 1993) defined biomechanics as the science that examines the internal and external forces acting on the human body and the effects that are produced. "Modern" biomechanics (Allard & Blanchi, 2000) has moved beyond the frameworks of mechanics and traditional human biology and is considered to be the application of physics to the study of all living systems, to the study of the forces generated by or acting on the organism and the effects on its movement or deformations (Figure 1).

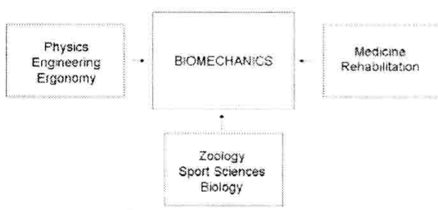

Figure 1. Biomechanics is at the crossroads of basic and applied sciences, and medical and natural sciences (Allard & Blanchi, 2000).

The main goals of biomechanics are to optimize performance, reduce injury, and adapt equipment to human use (Allard & Blanchi, 2000; Bartlett, 2005, 2007; Elliott, 1999). Biomechanics has traditionally analyzed performance optimization using a hierarchical model, presenting causal mechanisms between the different levels and elements of performance (Figure 2 for an example in swimming).

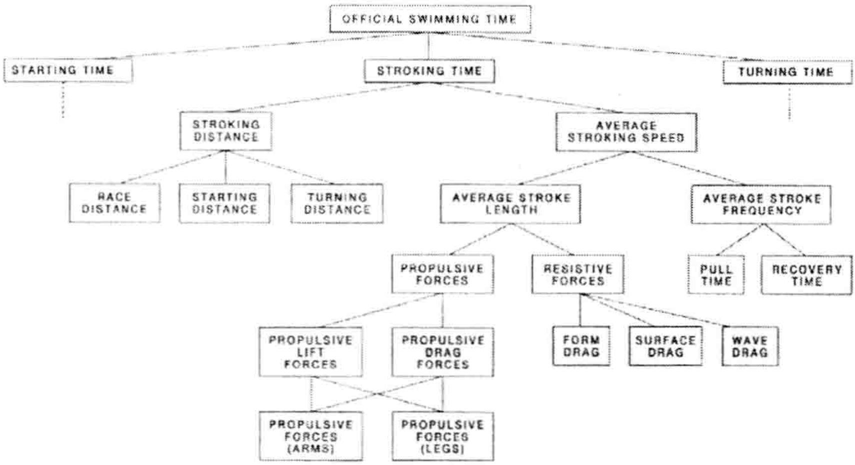

Figure 2. Hierarchical model of swimming performance (Hay, 1993).

However, a recurring criticism of biomechanics is its overreliance on description, especially as this approach segments performance elements using a hierarchical and deterministic model instead of examining the interactions between the elements, which might provide better explanation of the functional aspects of movement (Elliott, 1999; Glazier & Davids, 2009; Glazier et al., 2006). Several recent studies and reviews in biomechanics (Bartlett, 2005, 2007; Bartlett et al., 2007; Davids & Glazier, 2010; Glazier et al., 2006; Hamill et al., 2000) have suggested the utility of moving beyond definitions of modern biomechanics and the reliance on hierarchical models to focus more closely on the functional approach of biomechanics according to a motor control background (Enoka, 2004). For example, in Bartlett's *Sports biomechanics: Reducing injury and improving performance* (2005), chapter 5: "*Aspects of biomechanical analysis of sports performance*" was introduced by a brief explanation of movement control. The author dealt with the problem of movement coordination by referring to Bernstein (1967) (p. 149) and then noted Schmidt's theory (1975) and perception-action coupling, citing Kelso (1984) and Williams et al. (1998) (p. 150 to 152). In *Introduction to sports biomechanics: Analysing human movement patterns*, Bartlett (2007) introduced the first chapter: "*Movement patterns: the essence of sports biomechanics*" by mentioning a "*novel approach to sports biomechanics...considering the constraints-led approach to studying human movements*" (p. XIX) while at the same time Davids et al. (2008) published a book on motor control and learning titled: *Dynamics of skill* *acquisition: A constraints-led approach*, showing that the constraint-led approach (introduced by Newell, 1986) can be used in both biomechanics and motor control.

Another example concerning the role of variability indicated the same tendency for biomechanical and motor control research to draw closer (Davids & Glazier, 2010). In a review article titled: "*Is movement variability important for sports biomechanics?*" in *Sports Biomechanics*, Bartlett et al. (2007) synthesized the studies on movement variability by covering the kinematic and kinetic analyses and then moving on to consider motor control from both ecological and dynamical systems perspectives. In fact, the keywords included "*constraints, coordination, movement variability*", which are more commonly used in motor control articles. Similarly, Hamill et al. (2000) published a review titled "*Issues in quantifying variability from a dynamical systems perspective*" in the *Journal of Applied Biomechanics*, and showed that the barrier between biomechanics and motor control was disappearing. In a collective work, *Movement system variability*, which was coordinated by Davids, Bennett and Newell (2006), all recognized motor control researchers, Glazier et al. (2006) wrote a chapter that removed once and for all the border between biomechanics and motor control: "*The interface of biomechanics and motor control: Dynamic systems theory and the functional role of movement variability.*"

With regard to variability, Glazier et al. (2006) indicated five reasons why biomechanics had ignored motor control in analyses of performance: (i) performance is often analyzed from a single trial or the best trial and not from the inter-trial variability, (ii) high performance implies motor invariance and thus inter-trial variability is of little interest—although it is of high functional interest from ecological perspectives of motor control, (iii) hierarchical models lead to reductionist thinking rather than systemic thinking, which is informative about the coordination modes underpinning performance, (iv) biomechanics researchers often work from the assumption that optimal motor solutions exist and thus they tend to gather all the data on a set of subjects for analysis and neglect to examine inter-subject variations, and (v) analyses often focus on a given moment in time (static) rather than over time (dynamic), which may mask performance variability due to external events.

Over the past ten years, most of these divergences have been noted, and biomechanics, physiology and bioenergetics (giving rise to a new name: biophysics; for its application in swimming, see Barbosa et al., 2010; Pendergast et al., 2006) and the neurosciences and psychology (Beek et al., 1995; Fig. 3) have drawn closer, to such an extent that new methods now focus on inter- and intra-individual variability (Button et al., 2006; Rein et al., 2010), data time series and their fractal dimensions (Delignières, 2009; Delignières & Torre, 2009;