review article
received: 2014-11-28

UDC 796.012:001.891

THE ROLE OF DYNAMIC SYSTEMS IN MOTOR DEVELOPMENT RESEARCH: JUST A METAPHOR OR A NOTABLE REALITY?*

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ABSTRACT

In the present article an application of a new theory of motor control in the context of motor development theories and research has been discussed. In a brief overview of traditional theories of motor development a neuro-maturational theory is mentioned along with the two prominent proponents − McGraw & Gesell. Bernstein's fundamental insights in motor control were emphasized, such as the concepts of degrees of freedom and synergies, along with his contribution to the measurement technology and quantification. Basic principles of dynamic systems theory and common concepts such as self-organization, patterns, attractors or non-equilibrium systems are briefly described.

In the main part, an example of research in motor development carried out in dynamical perspective was introduced. The chosen example was the body of the research performed by Thelen et al. (1982, 1984, 1990) on a newborn's stepping. The distinction between the maturational perspective in which all the sequences of motor development are the result of maturation of nervous system, and the dynamic perspective in which development is seen as a mutual interaction between a number of body systems, including neural and muscular systems, which continuously affect the movement although none of them dominate (Kamm et al., 1990) has been made.

Keywords: *motor development, self-organization, patterns, motor control.*

* The paper was previously published in the Proceedings Book of the 7th International Scientific Conference on Kinesiology, 2014,Opatija, Croatia and is re-published in this journal with permission of the Editorial Board of the Proceedings.

VLOGA DINAMIČNIH SISTEMOV V RAZISKAVAH GIBALNEGA RAZVOJA: SAMO METAFORA ALI POMEMBNA REALNOST?

IZVLEČEK

V aktualnem članku se razpravlja o aplikaciji nove teorije kontrole gibanja v kontekstu teorij in raziskav gibalnega razvoja. V kratkem pregledu tradicionalnih teorij gibalnega razvoja je teorija maturacije živčnega sistema omenjena skupaj z dvema znanima avtorjema – McGrawom in Gesllom. Poudarjen je Bernsteinov temeljni vpogled v kontrolo gibanja, kot so koncepti stopenj prostosti in sinergij, skupaj z njegovim doprinosom tehnologiji meritev in kvantifikaciji. Na kratko so opisani osnovni principi teorije dinamičnih sistemov in splošni koncepti, kot so samoorganizacija, vzorci, atraktorji in neravnotežni sistemi. V glavnem delu je predstavljen primer raziskave na področju gibalnega razvoja, izvedene v dinamični perspektivi. Izbrani primer so bile raziskave E. Thelen in sodelavcev (1982, 1984, 1990) na korakanju novorojenčkov. Opisana je razlika med maturacijsko perspektivo, v kateri so vse sekvence gibalnega razvoja rezultat zorenja živčnega sistema, in dinamičnim pogledom, v katerem je razvoj prikazan kot vzajemna interakcija med številnimi telesnimi sistemi, vključno z živčnim in mišičnim sistemom, ki kontinuirano vplivajo na gibanje, čeprav nobeden od njiju ne prevladuje (Kamm et al., 1990).

Ključne besede: *gibalni razvoj, samoorganizacija, vzorci, kontrola gibanja*

TRADITIONAL VIEW OF MOTOR DEVELOPMENT

Clark & Whittall (1989) in their historical overview of the field of motor development mention that the earliest studies in motor development had begun in the18th century but according to the most textbooks on motor development (e.g. Gabbard, 2000; Payne & Isaacs, 2001; Haywood & Getchell, 2001) the first relevant theories derive from a body of research performed by Arnold Gesell and Myrtle McGraw in 1930s and 1940s.

Gesell (as cited in Gabbard, 2000) based his theory on a belief that the development is the result of inherited factors and that no requirements or stimulation from the environment are needed. In his view, ordered genetic sequences exist, and they determine the growth of tissue and body structures but also behavior, which means that movements are the product of changes in neural formations.

Similarly, McGraw (1943, as cited in Haywood & Getchell, 2001) related changes in the motor behavior to the development of nervous system. For example, McGraw associated an infant's ability to lift the head to the newly established control of the cervical region (Kamm et al., 1990).

The heritage left by the maturationists, which is still in use, consists of the developmental norms or the milestones which a child has to attain in his or her motor development.

After the neural maturational perspective, some other theories appeared on the scientific scene, among the latest were information processing and ecological perspectives. A common aim in many motor development studies, disregarding the theoretical perspective was the understanding of the relationships between the neural structure and behaviour, which in this case means the acquisition of motor skills. It is the skill that can be considered "a central dogma for kinesiology" as well, since the famous lecture by McCloy (1940) up to the present time (Zelaznik & Harper, 2007; Clark, 1995).

DEVELOPMENTAL BIODYNAMICS

The development of the motor skills (e.g. changes in motor behavior) was also central to the new developmental paradigm that arrived on the scene, the theory in which the development is seen as a mutual interaction between a number of body systems, including neural and muscular systems, which continuously affect the movement although none of them dominate (Kamm et al., 1990). The new perspective, called by some theorists „developmental biodynamics", was grounded on the dynamic systems theory which had already influenced many disciplines and had made an impact on the research concepts in chemistry, biology, but also in social sciences.

Although the system thinking in the developmental sciences, or broader − in biology, has a long tradition (Waddington, 1957), the real conceptualization and research has been possible since the legacy of the Nicolai Aleksandrovich Bernstein was introduced to the western science in the late 1960s.

Bernstein was a Soviet physiologist who studied human movement and wondered how the human movement system which is composed of such a large number of components (in Bernstein's words – 10^2joints, 10^3 muscles and 10^{14} neurons) could control multiple degrees of freedom in producing skilled actions (Bernstein, 1967). Bernstein proposed that the motor system is organized by a formation of synergies, e.g. units defined over the motor apparatus that automatically adjusts to each other and to the changing field of external forces (Gelfand et al., 1971) or, explained more directly, related to the movement, synergy refers to the "muscle linkage or coordinative structure, defined as a group of muscles often spanning several joints that is constrained to act as a single functional unit" (Tuller et al., 1982, p. 253). Bernstein rejected the idea of one-to-one relations between the neural codes and the produced movement patterns and he assumed that the movements can come out of different muscle contraction patterns and, similarly, that certain muscle contraction pattern does not have to produce identical movements every time. He believed that while the body moves, different forces arise (e.g. centripetal and inertial) and gravity should also be taken into account. Thus, while the movement happens, the field of forces continually changes and the same muscle contractions may have different outcomes.

Besides developing the theory, Bernstein also enhanced the research in motor control, and therefore the motor development research as well, by introducing the new methods of movement quantification. Along with the new theoretical concept he has put forward kinematic analysis which allowed spatial and temporal description of movement (a broader technical historical description of Bernstein's contribution to the measurement technology can be found in Medved, 2002). Together with the electromyography, kinematic data provided much better insight in movement organization than the traditional, solely neural explanation.

PRINCIPLES OF DYNAMIC SYSTEMS APPROACH

Human surrounding, animate and inanimate world is full of patterns which evolve over time but how the order is achieved from such a complexity or, in other words, how the patterns are formed is not entirely understood. The dynamic systems perspective offers a view in which human behavior is governed by the generic processes of *self-organization*, which is the spontaneous formation of patterns and their change in the open, non-equilibrium systems (Kelso, 1995). That refers to the systems which are far from (thermal) equilibrium and exchanging energy, matter or information with their environment, and which cannot sustain without those sources. Self-organization can be found in numerous physical, chemical or biological systems but also in the inanimate world. A very suitable example for this particular article is the human brain which is in the context of self-organization as explained by Haken "the most complex system we know in the world. It is composed of up to 100 billion neurons (and Glia cells) which are strongly interconnected. For instance, a single neuron can have more than 10,000 connections to other neurons. The central question is: who or what steers the numerous neurons so that they can produce macroscopic phenomena such as the coherent steering of muscles in locomotion, grasping, vision i.e. in the particular pattern recognition, decision making etc." (2008, p. 2555). A description of the collective or coordinated behavior of complex systems, living things among them, requires rather abstract variables and physical-mathematical notions, such as *collective variables* (sometimes called *order parameters*), *attractor, stability, phase space* and so on. Avoiding technical jargon and equations of motion which are in the heart of the dynamical systems theory, a brief description related to motor behavior will be given.

Collective variables define coupling or coordinated behavior of a complex system. In the case of walking, for example, someone could describe the system on the level of many individual components such as muscles, tendons, neural pathways, and metabolic processes. On that level of observation, a system can behave in an extremely complex fashion but if the cooperative behavior among the parts exists the system can be described by alternating the cycles of swings and the stance of the feet (Thelen & Smith, 2006). Also, other collective variables like muscle firing or torque forces etc., are possible.

Attractor states are a further important property of self-organization. An attractor may be explained simply as a preferred state or a point in the phase space of the system. Open systems could exhibit almost an infinite number of patterns of behavior, but they usually tend to form only a few of them or even just one and when they settle in that pattern (a mode of behavior) they tend to stay in it. If they are perturbed, they tend to return back to that attractor. Again, walking could serve as a simple example. In the coupled alternative movement of walking, legs are in the so-called anti-phase or 180 degree out of phase relation. Other relations are also possible within a state space but people prefer the anti-phase relationship which is in that case an attractor of 180 degrees out of phase (Thelen & Smith, 2006).

Stability is one of the core concepts of motor control, i.e. technically related it is a system facility in accommodating perturbations (Newell & Corcos, 1993). However, when several attractors exist with different basins of attraction, what appears is *multi-stability*, a coexistence of several collective states for the same value of control parameter and an essential characteristic of biodynamics. When the control parameter changes smoothly, attractor also changes and at one critical point the attractor may change even qualitatively (Kelso, 1995). In physics this phenomenon is called *non-equilibrium phase transition*. Another important idea for the movement organization is that movement is *softly assembled*, expressed for a fist time by Kugler & Turvey (1987), also grounded on Bernstein's premise that motor actions have to be programmed on a very high abstract level, otherwise the control of many parts acting on local level along with their interactions and continually changing forces may prove to be overwhelming for CNS. Softly-assembled, indicates that parts which are included in motor action should be organized in regard to their properties, interactions and context (Turvey, 1990). In other words, neuroanatomical components are selected naturally in a way that their organization is adaptive, flexible, task specific and that (soft) assembly may quickly reorganize itself according to the changes in task demands.

DYNAMIC SYSTEMS THEORY IN DEVELOPMENTAL RESEARCH

One of the most prominent examples of the use of the dynamic systems paradigm in motor development is the work of Ester Thelen on newborns' stepping (Thelen & Fisher, 1982; Thelen et al., 1984; Kamm et al.,1990). The behavior emerges when an infant is held upright and slightly leaning forward with his or her feet touching the ground. In this position, an infant performs alternating leg movements in a manner similar to walking. In the view of neural maturation and reflex-based theories, that behavior was considered a primitive reflex which disappears after 4 to 6 weeks as a consequence of brain maturation.

Thelen and colleagues (1982, 1984) compared the stepping and kicking of infants using kinematics and EMG, and what they found was a remarkable similarity in the number of measures between these two patterns. EMG records showed phasic activation of tibialis anterior and rectus femoris in flexion while extension was passive. Temporal organization of movement was also very similar and the authors concluded that stepping and kicking in infants is isomorphic. Significantly, they also found some differences − a range of motions for kicking was greater than for stepping and during supine kicking and the hip extension was longer with smaller extensions. The differences were explained by the changes in biomechanics of the movement with the changes in posture related to gravity. Lying supine, infants' hip flexion is assisted by gravity when the thigh passes the 90 degree angle, and when it is held upright, gravity assists the extension during the entire movement. Authors concluded that external forces were modelling and shaping spontaneous leg movement. They also assumed that the weight gain caused a decrease in the number of steps produced by infants thus suggesting that the gain of strength is slower than the gain of weight which inhibited walking. Additionally, Thelen et al. (1984) manipulated weight in two ways, first by adding the small weights to the infants' legs − which suppressed stepping, and second, by submerging the legs in warm water until their feet touched the bottom − which increased stepping dramatically.

The hypothesis was that the "disappearing" reflex could arise not by a design present in the brain but by the interdependence of heavy legs and biomechanically demanding posture (Thelen, 1995), manipulations with mass "restored" or "inhibited" reflex.

In the above example body weight and composition were in the role of the control parameter which can cause disappearance of a newborn's stepping response. The growth of the tissue affected the system and caused a qualitative shift in behavior. The way behavior changed suggests the effect of *non-linearity* – even a small change in the control parameter at a critical value may cause a qualitative shift (Thelen,1995).

In the study of the infants' kicking movements, Thelen et al. (1984) emphasized that none of the contributing factor to the behavior (e.g. the arousal of the infant, the gravity, neuromuscular system) has an advantage over the systems in determining the description of the kick. Gravity contributed to the topology, torques varied with gravity and vigour, and adapts to each change, while the whole system varied with arousal. The coordination and the timing in the kicking movements were the emergent properties, which were not specified by the neural signals alone. There was no program for the kick in any of the sub-systems, the behavior emerged as a product of interaction of the components concerned to the action. Thus, while the behavior was not specified than emergent, the system was *self-organized*.

Organisms in the development are complex because they are constituted of very many components, these components are in continuous interaction among themselves and with the environment which produces changes in components and in the system in whole. That effect is called the *multicausality*. Coherence among patterns of the emerged behavior is achieved by the interaction between organismic components and the constraints which has been set by environment and without a causal priority (Thelen

& Smith, 2006). One of the most important features of complex systems, i.e. patterns of behavior, is their index of stability. Crawling, for example, is a behavioral pattern which is very stable in his temporal and kinematic characteristics. Infants use that behavior for locomotion when a certain level of strength and coherence of the hands-to-knee posture is developed but the strength and the balance still do not allow upright locomotion (Thelen & Smith, 2006). Crawling remains stable for several months and then gives way to standing or upright walking which is the next stable behaviour, in that transition variability increases and system becomes unstable (Clark, 1995).

Crawling was also not pre-specified by genes or wired in nervous system (Thelen & Smith, 2006) but self-organized in task-context of moving through the space, and later replaced by an efficient locomotor pattern.

"Development can be envisioned as a series of evolving and dissolving patterns of varying dynamic stability, rather than an inevitable march toward maturity." (Thelen & Smith, 2006, p. 281).

CONCLUSION

Pioneer developmentalists were interested in infants' development of control over movements; namely, they assumed that the motor milestones and the emergence of motor skills reflect only brain maturation and a genetically driven overall development. The dynamic systems theory in motor control aims to explain the behavior of complex systems in the physical or biological sphere, and it could be comprehended as a conceptual guide, research program or a formal theory. From the dynamic systems perspective, the central nervous system is not exclusively responsible for movement, they are rather a product of biomechanical and energetic properties of the body, environment and specific demands of the task. The relations between the components are not hierarchical − top down, but rather non-linear, self-organizing and flexible. The research in dynamic perspective has undoubtedly managed to reveal the richness and the complexity of development as a multiple, mutual, and continuous interaction of all the levels of the developmental system (Thelen & Smith, 2006).

In the words of Ilya Prigogine (Arts Meets Science, 2013), a Nobel chemist (awarded in 1977 for his work in non-equilibrium thermodynamics which included self-organization) "... instead of emphasizing stability and permanence, science should emphasize change and adaptation ... non-equilibrium can produce coherence, structures and very complex patterns which permit us to see, to understand much better a type of structures that we see in the world around us".

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