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Dynamical Systems Approach to Infant Motor Development: Implications for Epigenetic Robotics

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A dynamical systems approach to motor development is presented. It highlights the challenges faced by human infants as they discover the potential of the body to perform different goal-directed actions. Some of the same challenges may face robotic systems that are modeled on epigenetic processes. The different categories of goal-directed actions, such as locomoting and ingesting foodstuffs, may emerge as a consequence of energy transactions between the brain, the biomechanical properties of the body, and a highly structured environment. Each dynamical system for performing certain goal-directed actions, called an action system, is conceptualized as a temporary coupling of biological components for doing work.

Different action systems of animals and humans – such as orienting, locomoting, and appetitive behavior (eating and drinking) – are assembled from microscopic components. Complex biological systems, including social insects such as termites as well as vertebrates with internal organs, may rapidly reconfigure themselves to form particular structural arrangements, a process called self-organization. Self organizing systems are characterized by multiple levels in which interactions at one level result in the emergence of new properties at another that cannot be understood as a simple addition of their individual contributions. For example, the cellular interactions involved in neuromuscular communications are the basis for the respiratory pumping mechanism, but the functional properties of the organs of breathing emerge at the level of organ systems.

The human nervous system may have evolved a synergetic strategy similar to that apparent in early multi-cellular life: establishing temporary couplings between dynamical systems in order to harness available energy resources. The coupled dynamical systems underlying human motor behavior are assembled from different biological devices comprising the neural, circulatory, musculoskeletal and other systems. These devices include skeletal levers, muscular engines, elastic storage systems, and positive pressure pumps. How do human infants – and, by implication, epigenetic robots – develop the ability to use the devices inherent in the organs of the body for performing different categories of action?

By performing rhythmical behaviors, such as kicking or sucking, with a body that has a particular anatomical configuration, the self-organizing properties of these rhythms assemble into useful devices. Each of the assembled devices is a collection of dynamical systems coupled to each other with varying degrees of strength. These dynamical systems are described by equations of motion with tunable parameters. Infants may explore the effects of their own goal-directed efforts on what the body actually does, and the nervous system may tune system parameters to make the assembled devices stable and energetically efficient.

To illustrate the assembly and tuning of action systems during infancy, this talk focuses on two motor skills: locomotion and appetition (sucking, swallowing, and breathing). Data from my research on infant bouncing as well as learning to crawl are used to illustrate the process by which self-produced actions are transformed into a device for locomotion, a coupled spring-pendulum system. First, I consider data from longitudinal studies of infants learning to bounce while supported upright by a harness and spring. Effortful kicking assembles a mass-spring system with limit cycle dynamical properties. Exploration of the relation between kicking and bouncing over longitudinal sessions results in a change in infant behavior: infants become more likely to kick at the moment in the cycle of bouncing when potential energy is highest, its resonant frequency. At a "peak" session, successive bounces increase dramatically in length, and kicking force decreases, indicating that the system is at resonance.

A second aspect of locomotor development involves inserting opportunities for postural support with the ground surface into an ongoing limit cycle oscillatory process. For example, during brief periods of rocking while in a prone posture, all of the limbs are oscillating in phase. During rocking, the infant may discover that kicking keeps them "trapped" at a single location on the support surface. The bilateral asymmetry of hand use during this period may allow the infants efforts to reach forward with one hand while supporting the body with the other to break free of this biomechanical trap. In dynamical terms, the hand preference is a symmetry breaking process, and allows the system to alternate postural support on the right and left sides of the body, as is evident in crawling.

The discussion of a second action system, appetition, focuses on how coupling of the actions of the tongue, lips, jaw and pharynx to the respiratory cycle of inspiration and expiration assembles a biological positive displacement pump for moving air to the lungs and foodstuffs to the digestive tract. A particular challenge for newborn infants is that the oropharynx is a shared anatomical pathway. How does the experience of early breastfeeding and bottle feeding make it possible for the CNS to discover the couplings of the component rhythms that result in swallowing without taking fluid into the lungs? In order to insert safe swallows into the respiratory cycle, the CNS may explore the stable patterns of relative phase between sucking and breathing for "windows" during which swallows do not occur as air is entering the lungs. Data is presented on newborn infants coordination of sucking, swallowing, and breathing during breastfeeding. Swallows are not randomly distributed during each complete cycle of respiration, but rather are attracted to a relative phase of either 0 degrees or 180 degrees. This suggests that the intrinsic dynamics of ongoing respiratory activity create phase windows during which swallows are safe. The bistable dynamics of coupled oscillators may provide a means for rapidly switching the organization of the pump so that swallowing and breathing do not occur simultaneously.

The discussion of appetition concludes with presentation of a computer-controlled system for regulating milk flow among premature infants and other clinical populations who have difficulty coordinating sucking, swallowing, and breathing.