Opinion

Cognition from the bottom up: on biological inspiration, body morphology, and soft materials

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Traditionally, in cognitive science the emphasis is on studying cognition from a computational point of view. Studies in biologically inspired robotics and embodied intelligence, however, provide strong evidence that cognition cannot be analyzed and understood by looking at computational processes alone, but that physical system–environment interaction needs to be taken into account. In this opinion article, we review recent progress in cognitive developmental science and robotics, and expand the notion of embodiment to include soft materials and body morphology in the big picture. We argue that we need to build our understanding of cognition from the bottom up; that is, all the way from how our body is physically constructed.

Introduction

The classical approach to the study of cognition advocates a deliberate abstraction from the physical realization of a cognitive system to the level of computation or information processing* [1–7]. In a recent paper this abstraction was characterized as follows: 'cognitive science has been dominated by a view of cognition as computation over mental representations' ([8], see p. 202]. This view has been very productive, at least in the initial stages of cognitive science. However, over the past two decades many criticisms have been voiced and alternatives have been proposed integrating concepts such as self-organization and embodiment; that is, the reciprocal and dynamical coupling among brain, body, and environment [8–18]. If we take, for example, the characterization of cognition found in [8] as the 'exercise of skillful know-how in situated and embodied action' (see p. 202), it is clear that this has little to do with information processing in the classical sense – a conceptual turn (or rather, a paradigm shift) whose import can hardly be overestimated.

Although there seems to be increasing agreement that the body plays an essential role in cognition (see, for instance, any of the references listed above), there has been relatively little work on detailing what the connection between brain and body looks like, how it shapes and drives our actions, and how it manifests itself in brain processing and behavior. In this opinion article, we attempt partially to fill this gap by discussing some essential prerequisites for higher-level cognition and intelligent behavior to emerge. We do so by giving illustrations and case studies from artificial intelligence, robotics, and human behavior. It turns out that robots can serve as highly productive tools to investigate fundamental issues in cognitive science. Moreover, following a recent trend in biologically inspired robotics, we expand the notion of embodiment to include soft materials and body morphology in the big picture. The main challenge is to connect two seemingly disparate areas: morphology and materials on the one hand and intelligence and cognition on the other.

Not only brains, but entire organisms

Traditionally, biological inspiration in the cognitive sciences has centered mostly on the modeling of brain areas and psychological phenomena such as memory, perception, language, categorization, and learning using methods from neuronal information processing (e.g., [20–24]). Biological inspiration in robotics, however, has not only focused on computational processes occurring in the brain but has incorporated the behavior of the entire (artificial) organism. By building physical models of animals, biologically inspired robotics (or biorobotics for short) has been advancing our understanding of locomotion, orientation and navigation, manipulation, perception, and actuation – areas where biological beings often outperform robots, which is why many engineers feel that if they understand biological principles and apply them to robots, they will be able to build more adaptive machines (e.g., [25–27]).

Exploiting materials: 'soft robotics' and morphological computation

An important characteristic of biological as well as robotic systems is their existence as physical (embodied) entities

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*Although some researchers (e.g., [19]) make a distinction between computation and information processing, for the purpose of the present paper, where the focus is in essence on embodiment, we take the two terms to be roughly equivalent.

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Box 1. Morphological computation

Every computational process, artificial or natural, has its origin in physically grounded dynamics such as electrons moving on a silicon chip or action potentials in a biological brain. Such dynamics forms the basic substrate, so to speak, for all of the processing from which ultimately something like cognition can emerge. Although computational processes determine the relationship between input and output, it is unclear where they occur and how they come about when considering the intelligent adaptive behaviors of concrete physical systems embedded in the real world (e.g., in animals or robots).

Let us take, for example, human bipedal locomotion, which is an inherently complex control problem for the brain. It has been shown that a robot, with properly designed body morphology, is capable of self-stabilizing natural bipedal locomotion, without actuation and control, by exploiting the passive dynamics of the mechanical body structure alone (e.g., [65]). By contrast, bipedal locomotion is also achievable using a more complex computational approach such as sensing the environment, planning, making decisions about the next step, and carefully controlling the whole body to place a foot with very small impact on the ground. Whereas the distinction between control or computational processes and physical ones is clear in the second example, it is blurred in the case of the first because all of the 'control' is incorporated into the morphology of the robot. Stated provocatively, there is no particular location where 'the memory of passive dynamic walking' can be found within a cognitive architecture: it is distributed throughout the entire system – in the length of the limbs, the weight distribution, the shape, and the frictional properties of the materials. Similarly, humans can dynamically adjust the stiffness of the muscles to meet the demands of the situation: low tension when the limb is loosely swinging, high tension to cope with impact in walking or running.

An important implication from the examples above is the fact that computation or information processing in the Turing or Shannon sense needs to be extended [14,65,66,70]. The computation implemented in the morphological domain tends to have several unique characteristics; for example, it is typically energetically efficient and very fast and has low cost. It can be also scaled up such that much more complex systems comprising many DOFs can be handled by a simple controller. For example, although operated by only one or two actuators, the octopus arm (Figure 1F) or the universal gripper (Figure 1G) can exhibit infinite variations of possible postures or configurations to achieve their grasping and manipulation tasks because they are exploiting the adaptive characteristics of their soft bodies. Other examples that demonstrate the interchangeable nature of computational processes and morphological properties include soft grasping (Figure 1D) and a tendon-driven robot (Figure 1E). Often, through morphological computation, sophisticated behavior can be achieved with much simpler computational architectures.

It is important to understand the trade-offs in the design process: implementing a particular functionality (e.g., coping with small perturbations) by means of morphological and material properties (e.g., by using a spring) can increase efficiency and speed, but at the cost of a loss of flexibility. The latter, however, can be partially recovered through morphologies and materials with changeable characteristics (e.g., dynamically varying the stiffness of the muscles or the spring constant).

in the real world. Such systems have a particular shape or body morphology, are built (by evolution or through an engineered construction process) from certain materials, are endowed with sensory and motor systems, and are embedded within their respective ecological niches. However, biological systems, in contrast to artificial ones, especially robots, are made for the better part of soft materials (even in humans, the rigid skeleton comprises less than 15% of overall body weight; [28]). It stands to reason that soft materials (apart from the enormous plasticity of the brain) are largely responsible for the adaptivity, robustness, and resilience found in nature. It turns out, for example, that functionalities such as stabilizing the body, coping with impact in walking, or adapting to the shape of an object while grasping can often be partly taken over by morphological and material characteristics; for example, the damped elasticity of the muscle–tendon system or the deformable tissue in the hand and on the fingertips. It is as if the brain were outsourcing some of the control – or computation – to morphology and materials, which is why this phenomenon is called morphological computation (Box 1). In this way, processes such as coping with small mechanical perturbations caused by unevenness in the ground, which require extremely rapid responses, can easily be taken care of by the body. Drawing from these observations and enabled by a combination of new materials and fabrication technologies, an emerging interdisciplinary subfield of biorobotics – soft robotics (Box 2) – has been exponentially gaining momentum over the past few years, as demonstrated by the many novel results, insights, and fascinating robots that have been produced (Figure 1). However, what has been missing so far is an understanding of the relation of soft robotics to cognition and intelligence.

Connecting cognition, morphology, and materials

Cognition can be studied, in essence, at three different timescales: (i) the 'here and now', which investigates the mechanisms of how, for example, grasping is achieved; (ii) the developmental timescale, which studies how these abilities come about through learning and maturation of the organism; and (iii) the phylogenetic timescale, which looks at the evolution of organisms over many generations (Figure 2) (see [14], derived from [29]). As we argue here, a developmental/learning point of view provides exactly the necessary concepts to bridge the gap between cognition, morphology, and materials. Starting with the evolutionary perspective, we introduce the different timescales and discuss how they interact.

What we now call cognition or intelligence (and the brain, its physical 'substrate') has always evolved as part of a complete organism that had to survive and reproduce in the real world. Because the body is the only way in which organisms can communicate with the environment, we have to investigate how brain, body, and environment interact to understand brain–body coevolution. Embedded into the evolutionary cycle there is a process of ontogenetic development that gets its initial conditions from evolution but is continuously shaped by physical (and social) interaction with the current environment (e.g., [30,31]).

Simulating mind–body coevolution

The plethora of compelling designs brought forth by biological evolution has always been a source of inspiration for researchers and engineers and led to the inception of the field of artificial evolution. In the 1960s, 1970s, and 1980s this was mostly about using computer programs for

Box 2. Soft robotics

In recent years, a new field in engineering has been emerging and growing rapidly – 'soft robotics'. Soft and deformable structures are crucial when dealing with uncertain and rapidly changing task environments. Unsurprisingly, biological systems largely comprise soft, deformable materials [26,67–69]. Softness can dramatically simplify interactions with the environment; for example, grasping and manipulation of objects of unknown shape, locomotion in rough terrains, and physical contacts with living cells and human bodies.

Soft robots typically have unique characteristics compared with conventional rigid robotic systems: they have elastic and deformable bodies that entail a large (often infinite) number of DOFs; and they have continuum bodies with no clear separation between components such as sensors, actuators, and supporting structures (e.g., skeletons). They often comprise unconventional smart materials such as hydrogels, conductive polymers, or temperature-sensitive alloys that can potentially endow passive structures with sensory–motor capabilities. Robotics researchers are investigating these physical properties because conventional rigid-design strategies are known to considerably limit robots' capabilities, especially in uncertain, unstructured, and dynamic task environments.

Owing to the rapid development of novel fabrication techniques and the availability of smart materials, there have been many achievements in soft robotics that are also highly relevant to cognitive science. For example, a novel design method for soft electronics was applied to construct bendable photoreceptor arrays [71]. Flexible reconfiguration of photoreceptor geometry allows us to investigate the influence of visual sensor morphology, which has been shown to perform a kind of preprocessing for the brain [i.e., a morphological computation (Box 1)].

On the motor side, pneumatically driven actuators are often used in soft robotics applications because they are not only small, powerful, and simple to fabricate, but are also easy to control for a large variety of tasks; for example, in snake-line robots for locomotion in complex environments, as soft exoskeletons [72], and in robotic hands for grasping unknown objects [73]. Soft robotics research is also necessary for 3D printing because constituent materials have to be liquefied and properly deformed into target shapes. This technology can be used to change dynamically the mechanical properties of tactile sensors to adjust sensitivity and sensing range *in situ* [74]. All of these case studies imply that sensory–motor skills and the cognitive abilities such as categorization and body schema that are built on them are considerably influenced by the specifics of morphology and materials: they are distributed throughout the system, not centralized in a cognitive architecture.

automated problem solving[†], but later these methods started to be used in robotics as well [32–36]. The standard approach has been to take a particular robot and to evolve its controller, typically a neural network. Interesting results have been achieved, but there was the serious constraint that the body could not evolve (thereby giving up a huge adaptive potential), which was obviously not the case during biological evolution. Investigators pioneered by Karl Sims [37] started to develop systems for mind–body coevolution that often came up with unexpected morphologies and displayed fascinating behaviors (e.g., [38,39]). Today, these systems can, for example, perform navigation, locomotion, foraging, and categorization tasks and are able to compete for 'food', which is why some researchers call these systems 'minimally cognitive' [10]. However, the gap between robotics and cognitive science remains.

As mentioned above, biology teaches that the mind has not evolved in isolation, in a kind of 'algorithmic ether', but as part of a complete organism. However, it tells us little about the details of the interaction between mind and body. To start elucidating this aspect, let us look at some recent developments.

Perception through action: sensory–motor contingencies (SMCs)

In their seminal paper, O'Regan and Noë [40] discuss the crucial role of action for perception and in the development of higher-level cognitive capabilities. They introduce the concept of SMCs, which are essentially characterized as the structure of the rules underlying the systematic change of sensory stimulation produced by motor action. This idea can be traced back to John Dewey who in his influential essay entitled 'The reflex arc concept in psychology' argued that 'we begin not with a sensory stimulus, but with a sensori-motor coordination, the movement of body, head and eye muscles determining the quality of what is experienced' [41]. Dewey, in essence, proposed one of the most fundamental principles of intelligent behavior; namely, that every action has as a consequence patterns of sensory stimulation [14,42].

To understand how these patterns are induced, we need to look more closely at SMCs. The patterns of sensory stimulation generated depend on several factors: (i) the task environment (e.g., the object we are grasping); (ii) the physical nature of the sensors (e.g., visual through the eyes, haptic through the skin in the hand and on the fingertips); (iii) the placement and distribution of the sensors on the organism (eyes in the head facing forward, high density of tactile receptors in the face, on the lips, and in the hand and fingertips); and (iv) the particular action (holding a cup in the hand leads to very different sensory stimulation than does moving the hand over the edge of the cup).

Putting it all together: development

Let us now see how it all fits together. The Russian neurophysiologist Nikolai Bernstein, while pioneering the field of motor learning, asked the question of how the central nervous system of humans or animals learns to master a complex and varying musculoskeletal system with many redundant degrees of freedom (DOFs) to perform skillful movements [43]. Due to the large number of variables involved (at the anatomical, kinematic, and neurophysiological levels), trying to learn the control of all DOFs simultaneously turns out to be virtually impossible – a well-known issue that arises when dealing with huge high-dimensional search spaces dubbed the 'curse of dimensionality' [44]. Bernstein hypothesized that, in the developing or learning organism, many DOFs are initially 'frozen' or rigidly coupled together; for a reaching movement, for instance, we do not need to control all of the joints in the hand immediately – we need only a few in the shoulder and the arm (this reduction in DOFs is often visible as a stiffening of posture). Once reaching is in place, additional DOFs can be 'freed up' (for example, opening the hand while performing the reaching movement), thereby adding flexibility to the performance. In a sense, the learning process is historical;

[†] Frequently referred to as evolutionary or genetic algorithms.

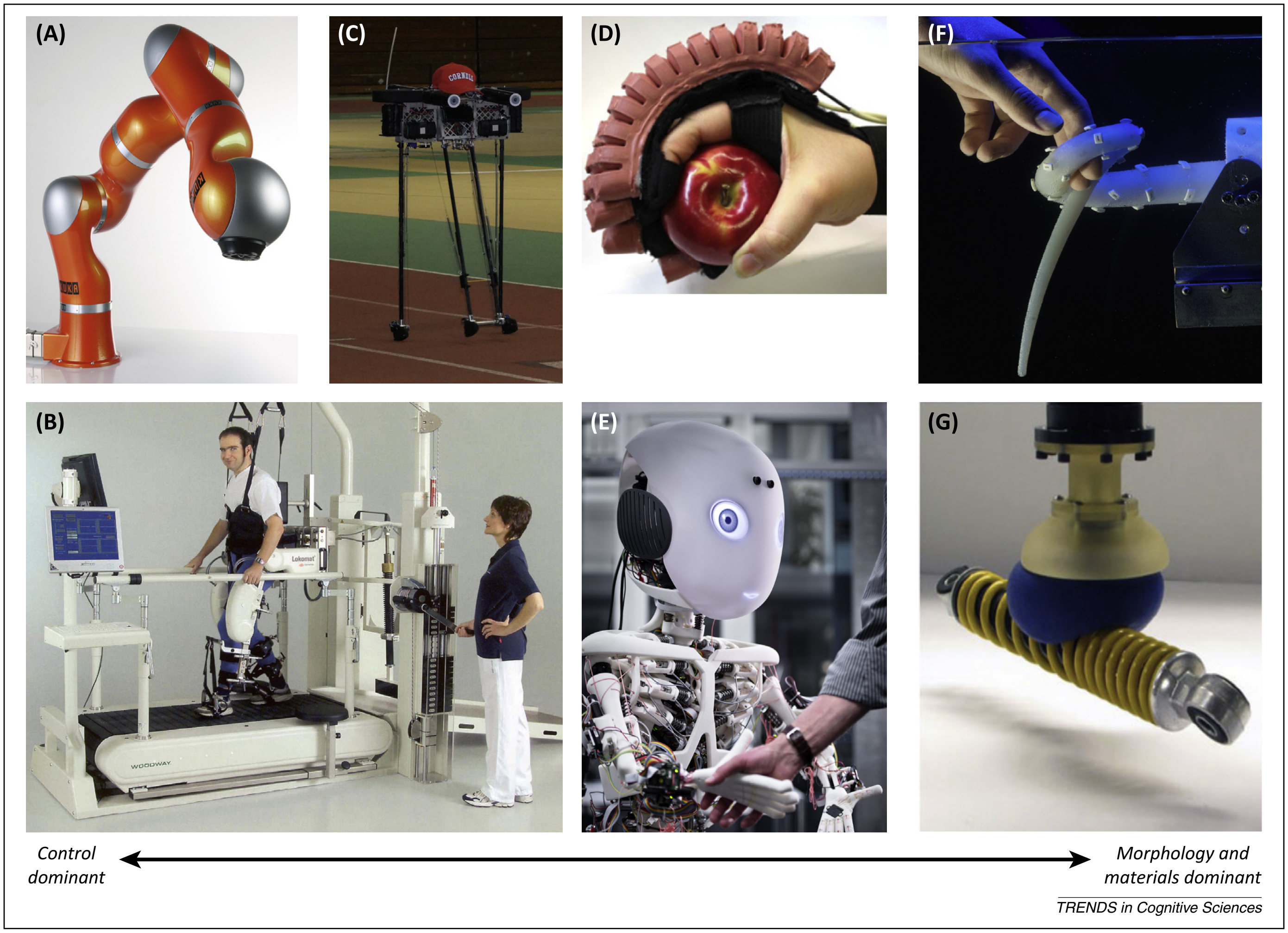

Figure 1. Trading control and materials: morphological computation. **(A)** An industrial manipulator, the KUKA lightweight robot, comprising rigid limbs and actuated joints to suppress mechanical dynamics for precise-positioning tasks. **(B)** The Lokomat$^{\text{TM}}$ robotic gait-training orthosis is an impedance-controlled exoskeleton with actuated hip and knee joints used for robot-assisted walking therapy (see also Box 3). **(C)** Passivity-based bipedal robot capable of energy-efficient walking (for more details, see Box 1). **(D)** Soft, wearable glove for grasp-assistive device. The actuators (red components around the fingers) are made of soft silicon that can be pressurized or depressurized to assist human grasping motions [75]. **(E)** Roboy, a humanoid robot comprising biologically inspired musculoskeletal structures. The robot uses tendon-driven actuation that enables soft and flexible motions of the skeletal structure. **(F)** Octopus-arm robot made of soft silicon and featuring tendon-driven actuation. The morphology and material of this arm provide high conformability of the structure to objects in contact [76]. **(G)** Soft gripper based on particle jamming. The gripper (blue component in the photograph) comprises a balloon filled with particles that generate grasping forces when the balloon is evacuated. The softness of the balloon allows the gripper to adapt to almost any shape of grasped object [77]. All of the robots (A–F) are capable of exhibiting adaptive behaviors, although the examples on the right exploit more morphological and material properties in their behaviors than those on the left.

that is, it builds on what has already been learned. A similar strategy seems to be used by babies and toddlers: they continuously adjust their body morphology by reorganizing their biomechanical DOFs, which in turn simplifies the control problem and accelerates motor learning. Also in this case, constraints on the search space are provided by the musculoskeletal structure of the body, biomechanical constraints, or, more generally speaking, the particular morphology.

The power of morphology and materials: illustrations

Although this ‘freezing–freeing strategy’ is a good conceptual model for illustrating the role of morphology in motor learning, the implications of the influence of morphology and material properties on the development of human cognition are more far reaching. A somewhat intuitive example is to think about the natural dynamics of our physical body. Assume that while standing, I let my arm swing loosely around my hip. Because of biomechanical constraints from the anatomy and the tissue (ligaments, muscles, and tendons) this movement requires little energy and little control because the control is – at least partially – incorporated into the shoulder–arm–hand system. The resulting trajectory of the hand in 3D space is highly complex, but there is virtually no explicit control about it. Despite the seemingly passive nature of the movement, due to the biomechanical bias, movement-related streams of correlated sensory stimulation are induced that, in turn, can drive motor learning (as illustrated by the ‘fetus simulations’ of Mori and Kuniyoshi [45] below).

The role of morphology and materials can also be explained in a slightly more complex motion-control task: grasping a glass. First, you look at the glass, then you reach for it; while approaching the glass you open the hand (preshaping) and finally you wrap your fingers around it by applying a certain force to the fingers. Note that by applying force, the fingers will automatically adapt to the shape of the object – you do not need to know its exact shape [46].

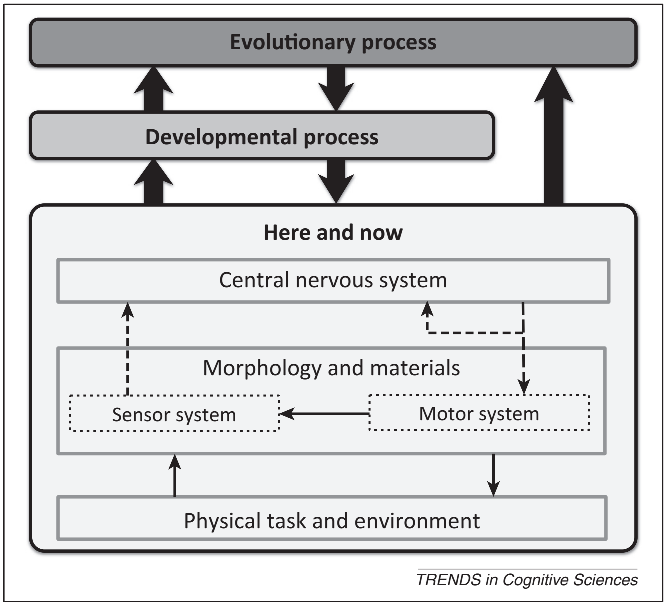

Figure 2. Cognition from the 'bottom up'. Behaviors of animals (and robots) emerge from interactions between physical task environments and sensor and motor systems with specific morphological and material properties. Signals from the central nervous system drive motor output and, through the morphology and material characteristics of the body, shape the behavior. A copy of the motor signals is sent to the brain that enables it to make predictions about the expected patterns of sensory stimulation. Through the agent's actions, correlated patterns of sensory stimulation are induced in different sensory channels. These interactions between the central nervous system, the sensor–motor system, and the task environment in the 'here-and-now' timescale are the outcome of evolutionary and developmental processes that occur at longer timescales. Because selection occurs at the here-and-now timescale (i.e., the phenotype interacting with the real world) there is a direct link from here and now to the evolutionary process.

Moreover, because the tissue in the hand and on the fingertips is soft, it will also adapt to the shape of the object passively, not centrally controlled – it is only the softness of the material that accounts for this. Lastly, because the skin is always a little humid, it has the right frictional properties. Imagine having to grasp the glass with metal thimbles on all of your fingers; it would be next to impossible – a nice illustration of what materials do for us.

Let us consider further what happens in the processing of sensory signals while grasping, for example, a cup in the hand. There is an evolutionary predisposition for the palm of the right hand to face left, which makes it easy to grasp the object.[‡] Grasping has several effects. First, I am (obviously) holding the cup in the hand. Second, because of the particular biomechanical constraints, the most natural and energy-efficient behavior is to move the hand toward the center in front of the body, which brings it into the middle of the visual field. In this way, task-relevant visual stimulation is induced (this would obviously not be the case if the eyes were physically located at the heels). Third, because of the grasp and thanks to the high density of tactile receptors in the hand and fingertips, rich patterns of tactile sensory stimulation are generated. Fourth, as a result of the proprioceptive sensory stimulation, I can feel roughly how big and heavy the cup is. Last but not least, visual and tactile information are integrated cross-modally; that is, the visual size and the felt size of the cup are combined into a single percept. This thought experiment illustrates the fact that the statistical regularities induced in the sensory channels depend on the morphology because the morphology constrains the actions, which in turn entails other patterns of sensory simulation, and therefore what is learned will be different for different morphologies.

Correlations through sensory–motor coordination

Through experiments with real and simulated robots, it has been shown that the sensory stimulation induced by a sensory–motor coordinated action (such as grasping or following a person with the eyes) incorporates statistical regularities and information structure [47–49]. Moreover, the sensory signals present in different channels are correlated across each other and this correlation is achieved through the physical interaction with the environment, not through processing in the brain. These patterns of correlated sensory stimulation constitute, so to speak, the 'raw input' that the brain processes to learn something about the world and to create coherent cognitive states. They are a prerequisite not only for any form of attention to filter out irrelevant signals from a massive sensory data flow, but also to form cross-modal associations that in themselves are necessary for concept formation (e.g., [17,31,49]). This implies that we can learn to predict the stimulation in one sensory channel (e.g., the haptic) from that in the other channel (e.g., the visual); by just looking at the glass, I already have an expectation of what it will feel like when I grasp it.

A cure for the curse of dimensionality?

Now we understand a little more about the influence of morphology, materials, and behavior on sensory stimulation and motor control, but how can we put these ideas together to understand human cognitive development or, more provocatively, to solve the problem of dimensionality?

A possible approach to address this challenge can be discussed in the context of the reafference principle. This principle, which can be applied to the control of movements, states that a copy of a motor command is stored together with the expected pattern of sensory stimulation and is compared with the actual feedback provided by the sensors (the reafferences). Based on the result of this comparison, the signal is then modified so that, over time, the real feedback matches the efference copy [50–52]. By applying the reafference principle, we can explore our own body dynamics; that is, we can establish the relation between the motor signals and the multimodal patterns of sensory stimulation induced by the movement. In other words, based on motor signals, we can build expectations that predict the consequence of particular actions before sensory feedback is available (see also Figure 2). Ultimately, this leads to the formation of a body schema [53] that can predict the consequences of motor actions and be used for achieving goal-oriented behaviors. Although many issues remain, this theoretical framework may support a systematic exploration of cognitive development in a bottom-up manner.

Changing morphology: the synthetic approach

There is a growing discipline – cognitive developmental robotics – that embeds models of biological, neural, and physical development in robots with the goals of

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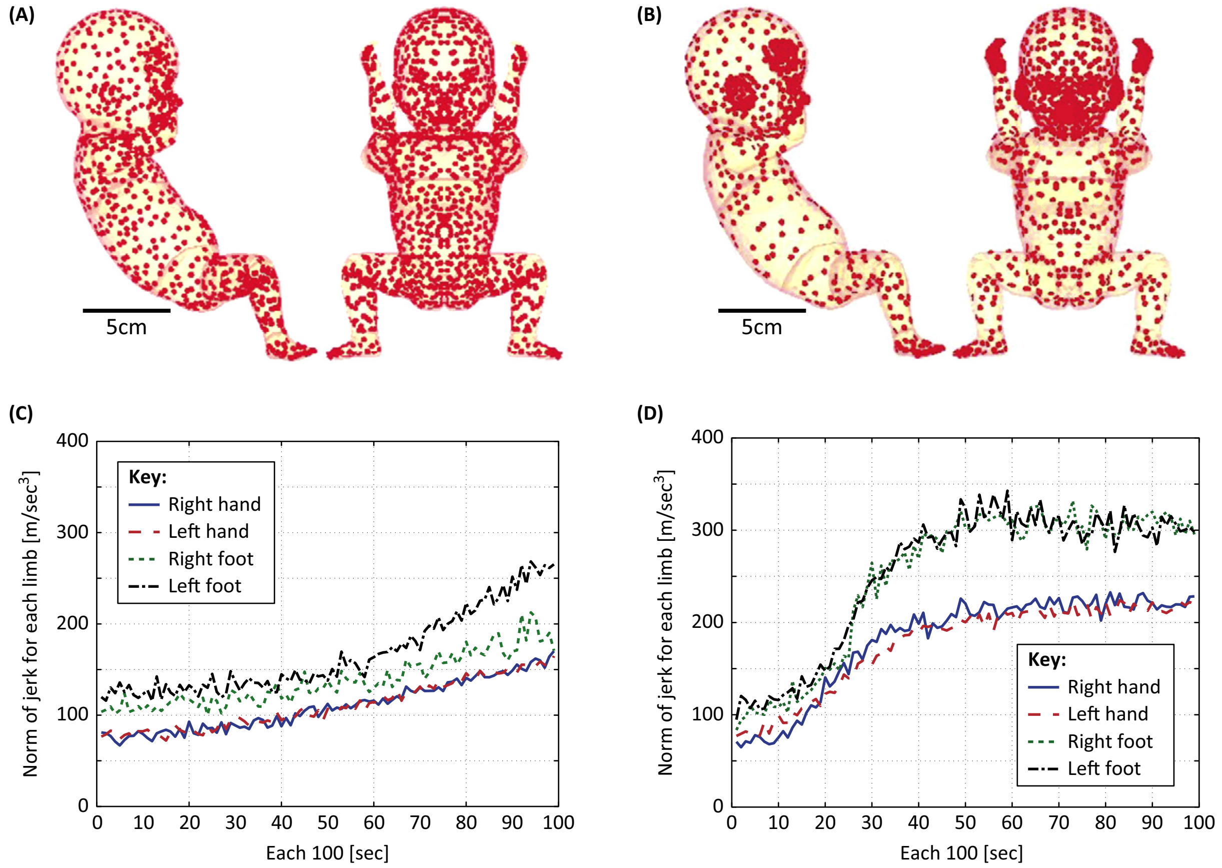
[‡] Note the interaction of the phylogenetic and here-and-now timescales (Figure 2).



TRENDS in Cognitive Sciences

Figure 3. The role of morphology in the development of sensory–motor behaviors. **(A,B)** Musculoskeletal model of a human fetus used to investigate the effect of tactile sensor distribution on the emergence of sensory–motor behaviors. Whereas the distribution in (A) is uniform (red dots) and therefore biologically implausible, that in (B) can be considered plausible. **(C,D)** The two graphs depict the norm of movement jerks (i.e., changes in acceleration) of the hands and feet over time. Because the sensory–motor coordination of these models is the result of a process of self-organization, emergent behaviors are strongly dependent on how the tactile sensors are distributed. Qualitatively similar behaviors can often be observed in human fetuses. Adapted from [45].

understanding human cognition and designing artificial cognitive systems [54–56]. The theoretical underpinning of this research endeavor is that, because phenomena occurring at developmental timescales are hard to study experimentally, it is necessary to adopt an unconventional strategy, also called the synthetic approach, that relies on building virtual agents (e.g., simulated animals, bioinspired robots) and analyzing their behaviors [14].

An illustrative recent case study is the simulation of a ‘fetus’ that was used to investigate the influence of sensor morphology on motor development. Because we are so accustomed to our own body morphology, to the physical nature of our senses (vision, audition, haptics, and proprioception), and to the distribution of the sensory receptors on the body (eyes in the head facing forward, high density of touch sensors in the hand, on the fingertips, and in the face), it is hard for us to imagine how it could be different. But let us, for the sake of the argument, assume that their distribution could be modified. How would this affect the developmental process? Mori and Kuniyoshi [45], in groundbreaking work, simulated the neuromotor development of a fetus in the uterus with different distributions of haptic sensors. With a natural (nonhomogeneous) distribution, the fetus developed ‘normal’ kicking and jerking movements (i.e., similar to those observed in a human fetus), whereas with a homogeneous allocation it did not develop any of these behaviors (Figure 3). This is a dramatic illustration that the morphology – of which the physical nature and placement of the sensors on the organism is an essential part – can crucially affect motor development because the patterns of sensory stimulation resulting from initially random movements will be very different for different distributions, which in turn influences neural development [57]. It also shows the power of development (natural and artificial) and of how sophisticated, seemingly goal-directed behaviors can emerge from random ones. These processes are enabled through the morphological constraints of an embodied system.

Reflexes from self-organization

Although it is already intriguing to study the influence of sensor morphology on the development of cognition, other developmental phenomena can also be explored. For instance, simply lifting a leg from the ground requires the concerted activation of many muscles and muscle groups responsible for the movement of the knee and hip joints. Moreover, as the motion starts, sensory–motor coordination, mostly at the level of spinal reflexes, kicks in: every muscle–tendon complex is equipped with numerous sensory receptors such as muscle spindles and Golgi tendon organs (which signal changes in muscle length and muscle tension) that form synapses directly with motor neurons in

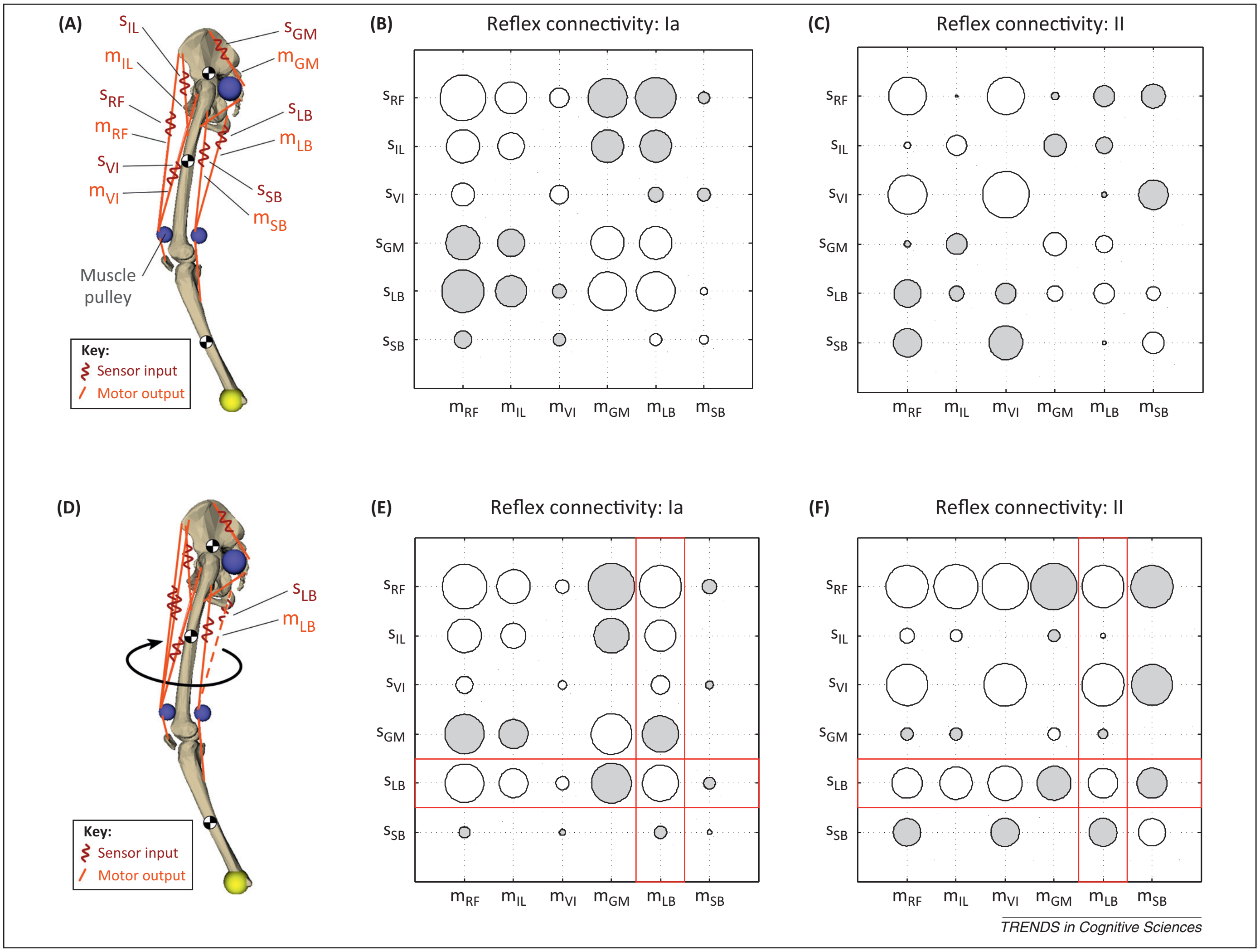


Figure 4. The role of morphology in a neuromusculoskeletal system. **(A)** Biologically plausible musculoskeletal leg model comprising a pelvis as well as upper- and lower-leg segments. Six muscle–tendon elements (shown by red lines) are implemented in this model, each of which has motor neuron output (labeled m_{**}) and sensory input (labeled s_{**}). **(B,C)** Diagrams of sensory–motor connectivity from an experiment with the model shown in (A), which corresponds to human reflex responses. The larger the circle in this diagram, the stronger the corresponding sensory–motor connectivity; gray circles represent excitatory and white circles inhibitory connections. The connectivity was obtained by a self-organizing scheme (unsupervised learning of sensory–motor mapping) through seemingly random perturbation of muscles. **(D)** Modified leg model in which one of the six muscles is misplaced to the other side of the upper-leg segment, corresponding to an alteration in morphology. **(E,F)** Reflex circuits obtained from an experiment with the model shown in (D). Due to the misplaced muscle, a different connectivity is learned, especially in connections (synapses) that are directly influenced by the misplaced muscle (indicated by red lines). Self-organization of connectivity was observed only when a biologically plausible muscle model (Hill type) was employed. Adapted from [58].

the spinal cord that, in turn, regulate the contraction of the muscles involved in the movement. The spinal reflexes also ensure that the muscles do not act against each other or that muscle tension does not exceed the limit beyond which damage to muscle fibers or joints may occur. These basic sensory–motor coordination circuits are the foundation of all motor behaviors in humans, but it remains largely unknown how they develop.

To get a better grip on the mechanisms underlying the development of such reflexes, Marques and his colleagues [58,59] used a neuromusculoskeletal model of a leg embedded in a simulated environment (Figure 4A). With this setup they conducted a series of computational experiments to study under what conditions basic reflexes can self-organize. They found that, under particular conditions, spontaneous motor activity in each muscle of the musculoskeletal model could lead to correlations in the sensor and motor signals (Figure 4B,C). These regularities were picked up by an unsupervised learning scheme, which resulted in the emergence of reflex circuits similar to those found in human fetuses. As one might expect, different morphological configurations of the musculoskeletal system led to the emergence of different types of reflex circuit (Figure 4D,E,F). An important discovery was that self-organization could occur only when the so-called Hill-type muscle model was used (i.e., one of the most widely used biologically plausible muscle models in biomechanics); self-organization was not observed when a series elastic actuator model was used (i.e., one of the most popular models in robotics research). The latter point will require additional investigation in future research.

This computational experiment shows that morphology influences cognitive processes not only through physical attributes or constraints such as where sensory receptors or muscles are located on the body, but also through how body parts such as muscles and tendons react dynamically to given stimuli through bodily material properties. In other words, without a better understanding of such material aspects of embodied systems, we will not be able to fully understand how the body shapes the development of the central nervous system.

Open questions

We believe that we have convincingly argued that the morphology and the material properties of the body and neuronal information processing (or better, brain dynamics) are tightly interconnected because the raw inputs (i.e., the patterns of sensory stimulation) are generated through the physical interaction of the body with the environment. However, many tough questions remain.

First, will we ever be able, using this bottom-up approach, to engineer systems that are capable of mastering complex cognitive skills, such as language or mathematics, and that can handle or 'understand' other abstract concepts like responsibility and democracy? For example, in a highly provocative and inspiring essay George Lakoff and Rafael Nunez [60] (see also [61]) suggest that, by building on the notion of conceptual metaphors, this will indeed be the case. By conceptual metaphor, they refer to the understanding of an abstract idea in terms of a physical one; for example, framing the abstract idea of 'importance' in terms of 'size' or the mathematical concept of a 'set' in terms of a 'container'. Much of the work presented by Lakoff and Nunez is grounded in empirical research (e.g., studying mathematicians' gestures while explaining an abstract concept like a limit or infinity) but additional evidence will most certainly be required. We are convinced that robots and embodied-agent simulations can provide a highly productive test bed to deepen these ideas, because in robots and simulations, in contrast to humans, all motor commands and sensory stimulation can be recorded and analyzed in detail.

Box 3. Human–robot interfaces

A growing number of robots are in close physical contact with humans (e.g., robots used in rehabilitation). The traditional approach to ensure safe interaction relies on hard mechanical constraints and appropriately designed control systems (e.g., based on impedance or force control). To minimize interference between movements of the user and those of the robot, the parameters of the controller are optimized to match the dynamics of the human sensor–motor control with those of the robot.

Despite their popularity, the design of purely control-based human–robot interfaces still faces many challenges [78]. Often, because conventionally controlled robots inappropriately constrain the patient's voluntary movements, there is an interference with natural motor function. Moreover, constraints on the user's natural DOFs (e.g., in the case of a rigid exoskeleton used for rehabilitation) result in neural adaptations with a gradual reduction of muscle activity over time, as well as patterns of proprioceptive and tactile sensory stimulation that differ from those induced while performing unconstrained movements [79]. The implication is that the learned SMCs differ from those required to perform activities of daily living (the goal of any meaningful therapeutic intervention). Lastly, the timescales associated with the delays intrinsic to the human sensory system involved in movement (e.g., conduction delays, neural processing delays, the low-pass filter properties of muscles; [80]) place an additional requirement on human–robot interfaces that is not easily tackled by control alone.

As argued in this opinion article, a way out of this impasse is by employing soft materials and adequate robot morphologies. Soft robots with less rigid actuators, low mechanical inertia (e.g., pneumatic contractile elements; Figure 5), and elastic joints (e.g., tendon-driven actuation) are intrinsically safe in interactions with humans and compliant to touch [75,81]. We conjecture that their passive compliance will provide a much better environment for humans to promote neural plasticity and re-educate the neuromuscular system during rehabilitation. By introducing fewer constraints on the user's natural DOFs and offering tight or even delay-free interfaces, soft robots will allow better matching of reafferent sensory feedback to synchronized voluntary motor actions. We hypothesize that this might support functional compensation or even help rebuild a working body schema, which will improve patients' sensory–motor behaviors, cognitive skills, and, in turn, their performance in activities of daily living.

Second, what is the role of human interaction in the developmental process and how does it influence sensory–motor learning and skill acquisition? There is much evidence that sensory–motor tasks are learned more quickly through instruction, observation, and imitation, as examples of interactions between humans [42]. However, how should we construct smart machines or human–robot interfaces to enhance regularities in sensory inputs and elicit neural responses that promote motor learning and faster recovery after debilitating illnesses (see also Box 3 and Figure 5)?

Third, we have talked about concept formation by building cross-modal associations. What about the function of language in this process? There are fascinating experiments on language acquisition investigating this process, although the results remain preliminary. For example, Steels and colleagues, using partially embodied agents (physically movable cameras) demonstrated that, in a naming game played over the Internet, after a number of interactions a common vocabulary emerged in a population of agents [62,63].

Fourth, do organisms with different morphologies develop different kinds of cognition? For example, do congenitally blind children, because of their different 'morphology' (sensors) acquire other concepts and think differently compared with children with normal vision? According to the ideas presented in this opinion article, we can, without attributing value, expect rather fundamental differences (see also Mori and Kuniyoshi's simulation experiments [45]). A similar question can be asked about children with movement disabilities. Again, because the patterns of sensory stimulation that form the basis (the raw material) for learning will be affected according to our earlier discussion, we can expect the cognitive structures that develop to be different. We can also employ the framework presented to assess the potential forms of (artificial) cognition in robots. Given that robots, in particular humanoid ones, will increasingly move into our everyday lives and we have a strong tendency to project our own ideas onto them, it seems especially important to understand the fundamental differences of their cognitive capabilities due to their entirely different morphologies.

Finally, returning to the computational view of cognition, what is the relation between the evolutionary designs of embodied forms of intelligence (humans and animals) and computational ones such as IBM's Jeopardy-playing software 'Watson' [64]? Morphological computation, by its nature of being implicit in bodily characteristics, does not have to 'take all potential situations' into account, so to

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Figure 5. Allegro^{TM}. A force-controlled bionic training partner featuring visual and haptic feedback, intrinsically compliant pneumatic actuation, forces and speeds matching those of humans, and a wide range of online sensory–motor testing and measuring facilities. The kinematic constraints and the interaction dynamics of the Allegro are designed to minimize interference with natural (unperturbed) movements of the user. Reproduced, with permission, from Dynamic Devices AG (http://www.dynamicdevices.ch).

speak (which is what makes it so efficient), because they are taken care of 'automatically': the spring will simply react to impact without control and the material on the fingertips will deform when a force is applied. In a disembodied computational approach, all potential situations have to be anticipated and rules have to be provided. Most likely, it will depend on the specific task domains whether a purely computational approach can be successful. Good examples are chess and manufacturing environments where (almost) everything can be anticipated.

Concluding remarks

Of course, we have not solved the big question of how cognition can be built from the bottom up or how it emerges from body morphology, soft materials, and the interactions of a natural or artificial organism with the world. However, we are beginning to see how the body – the morphological and material properties – and the mind mutually support each other in development, in learning to master a complex body, and in acquiring knowledge about the environment, which allow us better to perform and ultimately survive in the real world. The more you think about it, the more you marvel at how everything fits together and is mutually constitutive of what we call cognition or intelligence: studying one part without taking all of the rest into account does not make sense. Investigating the brain in isolation without taking morphology, materials, and environment into account will only tell us part of the story. It also teaches us very powerful lessons about how to learn from biology and how to build better robots.

References

1 Atkinson, R.C. and Shiffrin, R.M. (1968) Human memory: a proposed system and its control processes. In *The Psychology of Learning and Motivation: Advances in Research and Theory* (Vol. 2) (Spence, W.K. and Spence, J.T., eds), In pp. 89–195, Academic Press
2 Newell, A. and Simon, H.A. (1972) *Human Problem Solving*, Prentice Hall
3 Pylyshyn, Z.W. (1980) Computation and cognition: issues in the foundations of cognitive science. *Behav. Brain Sci.* 3, 111–169
4 Anderson, J.R. (1983) *The Architecture of Cognition*, Harvard University Press
5 Newell, A. (1990) *Unified Theories of Cognition*, Harvard University Press
6 Ashcroft, M.H. (1994) *Human Memory and Cognition* (2nd edn), Harper Collins
7 Pinker, S. (1997) *How the Mind Works*, W.W. Norton
8 Engel, A.K. *et al.* (2013) Where's the action? The pragmatic turn in cognitive science. *Trends Cogn. Sci.* 17, 202–209
9 Barsalou, L.W. (2008) Grounded cognition. *Annu. Rev. Psychol.* 59, 617–645
10 Beer, R.D. and Williams, P.L. Information processing and dynamics in minimally cognitive agents. *Cogn. Sci.* (in press)
11 Clark, A. (1997) *Being There: Putting Brain, Body and World Together Again*, MIT Press
12 Glenberg, A.M. (2010) Embodiment as a unifying perspective for psychology. *Cogn. Sci.* 1, 586–596
13 Pfeifer, R. and Scheier, C. (1999) *Understanding Intelligence*, MIT Press
14 Pfeifer, R. and Bongard, J. (2007) *How the Body Shapes the Way We Think – a New View of Intelligence*, MIT Press
15 Port, R.F. and van Gelder, T., eds (1995) *Mind as Motion: Explorations in the Dynamics of Cognition*, MIT Press
16 Shapiro, L. (2011) *Embodied Cognition*, Taylor & Francis
17 Smith, L.B. and Sheya, A. (2010) Is cognition enough to explain cognitive development? *Top. Cogn. Sci.* 2, 725–735
18 Varela, F.J. *et al.* (1993) *The Embodied Mind: Cognitive Science and Human Experience*, MIT Press

19 Piccini, G. and Scarantino, A. (2011) Information processing, computation, and cognition. *J. Biol. Phys.* 37, 1–38

20 Anderson, J.A. and Hinton, G.E., eds (1981) *Parallel Models of Associative Memory*, Erlbaum

21 Churchland, P.S. and Sejnowski, T.J. (1992) *The Computational Brain*, MIT Press

22 Ellis, R. and Humphreys, G. (1999) *Connectionist Psychology*, Psychology Press

23 Elman, J.L. *et al.* (1998) *Rethinking Innateness: A Connectionist Perspective on Development*, MIT Press

24 McClelland, J.L. and Rumelhart, D.E. (1986) *Parallel Distributed Processing: Explorations in the Microstructure of Cognition*, MIT Press

25 Iida, F. and Ijspeert, A. Biologically inspired robotics. In *Handbook of Robotics* (Siciliano, B. and Khatib, O., eds), Springer Verlag (in press)

26 Pfeifer, R. *et al.* (2012) The challenges ahead for bio-inspired “soft” robotics. *ACM Commun.* 55, 76–87

27 Zhou, X. and Bi, S. (2012) A survey of bio-inspired compliant legged robot designs. *Bioinspir. Biomim.* 7, 041001

28 Gropper, S.S. *et al.* (2009) *Advanced Nutrition and Human Metabolism*, Cengage Learning

29 Tinbergen, N. (1963) On aims and methods of ethology. *Z. Tierpsychol.* 20, 410–433

30 Goldfield, E.C. (1995) *Emergent Forms: Origins and Early Development of Human Action and Perception*, Oxford University Press

31 Thelen, E. and Smith, L.B. (1994) *A Dynamic Systems Approach to the Development of Cognition and Action*, MIT Press

32 Bongard, J.C. (2013) Evolutionary robotics. *ACM Commun.* 56, 74–85

33 Cliff, D. *et al.* (1993) Explorations in evolutionary robotics. *Adapt. Behav.* 2, 73–110

34 Floreano, D. and Mattiussi, C. (2008) *Bio-inspired Artificial Intelligence: Theories, Methods, and Technologies*, MIT Press

35 Husbands, P. and Meyer, J.A., eds (1998) *Evolutionary Robotics: First European Workshop, EvoRobot’ 98*, Springer Verlag

36 Nolfi, S. and Floreano, D. (2000) *Evolutionary Robotics – the Biology, Intelligence, and Technology of Self-organizing Machines*, MIT Press

37 Sims, K. (1994) Evolving 3D morphology and behavior by competition. *Artif. Life* 1, 353–372

38 Bongard, J.C. (2011) Morphological change in machines accelerates the evolution of robust behavior. *Proc. Natl. Acad. Sci. U.S.A.* 108, 1234

39 Lipson, H. and Pollack, J.B. (2000) Automatic design and manufacture of artificial lifeforms. *Nature* 406, 974–978

40 O’Regan, K. and Noë, A. (2001) A sensorimotor account of vision and visual consciousness. *Behav. Brain Sci.* 24, 939–973

41 Dewey, J. (1896) The reflex arc concept in psychology. *Psychol. Rev.* 3, 357–370

42 Wolpert, D.M. *et al.* (2011) Principles of sensorimotor learning. *Nat. Rev. Neurosci.* 12, 739–751

43 Bernstein, N. (1967) *The Coordination and Regulation of Movement*, Pergamon Press

44 Bellman, R.E. (1961) *Adaptive Control Processes: A Guided Tour*, Princeton University Press

45 Mori, H. and Kuniyoshi, Y. (2010) A human fetus development simulation: self-organization of behaviors through tactile sensation. In *IEEE 9th International Conference on Development and Learning*, pp. 82–87, IEEE

46 Bicchi, A. *et al.* (2011) Modelling natural and artificial hands with synergies. *Philos. Trans. R. Soc. Lond. B: Biol. Sci.* 366, 3153–3161

47 Lungarella, M. and Sporns, O. (2006) Mapping information flow in sensorimotor networks. *PLoS Comput. Biol.* 2, e144

48 Sperati, V. *et al.* (2014) Mutual information as a task-independent utility function for evolutionary robotics. In *Guided Self-organization: Inception* (Prokopenko, M., ed.), pp. 389–415, Springer

49 Pezzulo, G. *et al.* (2012) Computational grounded cognition: a new alliance between grounded cognition and computational modeling. *Front. Psychol.* 3, 612

50 von Holst, E. and Mittelstaedt, H. (1950) The principle of reafference: interactions between the central nervous system and the peripheral organs. *Naturwissenschaften* 37, 464–476

51 Crapse, T.B. and Sommer, M.A. (2008) Corollary discharge across the animal kingdom. *Nat. Rev. Neurosci.* 9, 587–600

52 Shadmehr, R. *et al.* (2010) Error correction, sensory prediction and adaptation in motor control. *Annu. Rev. Neurosci.* 33, 89–108

53 Hoffmann, M. *et al.* (2010) Body schema in robotics: a review. *IEEE Trans. Auton. Ment. Dev.* 2, 304–324

54 Weng, J. *et al.* (2001) Autonomous mental development by robots and animals. *Science* 291, 599–600

55 Asada, M. *et al.* (2009) Cognitive developmental robotics: a survey. *IEEE Trans. Auton. Robot.* 1, 12–34

56 Lungarella, M. *et al.* (2003) Developmental robotics: a survey. *Connect. Sci.* 15, 151–190

57 Singer, W. (1995) Development and plasticity of cortical processing architectures. *Science* 270, 758–764

58 Marques H.G. *et al.* From spontaneous motor activity to coordinated behaviour: a developmental model. *PLoS Comput. Biol.* (in press)

59 Blumberg, M.S. *et al.* (2013) Twitching in sensorimotor development from sleeping rats to robots. *Curr. Biol.* 23, R532–R537

60 Lakoff, G. and Johnson, M. (1999) *Philosophy in the Flesh: The Embodied Mind and its Challenge to Western Thought*, Basic Books

61 Lakoff, G. and Nunez, R.E. (2000) *Where Mathematics Comes From*, Basic Books

62 Steels, L. (1999) *The Talking Heads Experiment. Volume I: Words and Meanings*, Laboratorium

63 Steels, L. and Belpaeme, T. (2005) Coordinating perceptually grounded categories through language: a case study for colour. *Behav. Brain Sci.* 28, 469–489

64 Lally, A. *et al.* (2012) Question analysis: how Watson reads a clue. *IBM J. Res. Dev.* 56, 1–14

65 Collins, S. *et al.* (2005) Efficient bipedal robots based on passive–dynamic walkers. *Science* 307, 1082–1085

66 Hauser, H. *et al.* (2011) Towards a theoretical foundation for morphological computation with compliant bodies. *Biol. Cybern.* 105, 355–370

67 Kim, S. *et al.* (2013) Soft robotics: a bioinspired evolution in robotics. *Trends Biotechnol.* 31, 287–294

68 Majidi, C. (2013) Soft robotics: a perspective – current trends and prospect for the future. *Soft Robot.* 1, 5–11

69 Trimmer, B.A. (2013) Soft robots. *Curr. Biol.* 23, 639–641

70 Paul, C. (2006) Morphological computation – a basis for the analysis of morphology and control requirements. *Robot. Auton. Syst.* 54, 619–630

71 Floreano, D. *et al.* (2013) Miniature curved artificial compound eyes. *Proc. Natl. Acad. Sci. U.S.A.* 110, 9267–9272

72 Song, Y.S. *et al.* (2013) Soft robot for gait rehabilitation of spinalized rodents. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 971–976, IEEE

73 Martinez, R.V. *et al.* (2013) Robotic tentacles with three-dimensional mobility based on flexible elastomers. *Adv. Mater.* 25, 205–212

74 Nurzaman, S.G. *et al.* (2013) Active sensing system with *in situ* adjustable sensor morphology. *PLoS ONE* 8, e84090

75 Mosadegh, B. *et al.* (2014) Pneumatic networks for soft robotics that actuate rapidly. *Adv. Funct. Mater.* 24, 2163–2170

76 Margheri, L. *et al.* (2012) Soft robotic arm inspired by the octopus: I. From biological function to artificial requirements. *Bioinspir. Biomim.* 7, 025004

77 Brown, E. *et al.* (2010) Universal robotic gripper based on the jamming of granular material. *Proc. Natl. Acad. Sci. U.S.A.* 107, 18809–18814

78 Marchal-Crespo, L. and Reinkensmeyer, D.J. (2009) Review of control strategies for robotic movement training after neurologic injury. *J. Neuroeng. Rehabil.* 6, 20

79 Gordon, K.E. and Ferris, D.P. (2007) Learning to walk with a robotic ankle exoskeleton. *J. Biomech.* 40, 2636–2644

80 Franklin, D.W. and Wolpert, D.M. (2011) Computational mechanisms of sensorimotor control. *Neuron* 72, 425–442

81 Lens, T. and von Stryk, O. (2012) Investigation of safety in human–robot-interaction for a series elastic, tendon-driven robot arm. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 4309–4314, IEEE