Morphological Development in robotic learning: A survey

M. Naya-Varela[1], A. Faina[2], R. J. Duro[1].

[1]Integrated Group for Engineering Research,
CITIC (Centre for Information and Communications Technology Research)
Universidade da Coruña, Spain.

[2]Robotics, Evolution and Art Lab (REAL),
Computer Science Department
IT University of Copenhagen, Denmark

***Abstract*— Humans and animals undergo morphological development processes from infancy to adulthood that have been shown to facilitate learning. However, most of the work on developmental robotics considers fixed morphologies, addressing only the development of the cognitive system of the robots. This paper aims to provide a survey of the work that is being carried out within the relatively new field of morphological development in robots. In particular, it contemplates morphological development as the changes that occur in the properties of the joints, links and sensors of a robot during its lifetime and focuses on the work carried out by different authors to try to determine their influence on robot learning. To this end, walking, reaching, grasping and vocalization have been identified as the four most representative tasks addressed in the field, clustering the work of the different authors around them. The approach followed is multidisciplinary, discussing the relationships among developmental robotics, embodied artificial intelligence and developmental psychology in humans in general, as well as for each of the tasks, and providing an overview of the many avenues of research that are still open in this field.**

I*ndex Terms*—cognitive robotics, morphological development, robot learning, sensory-motor coordination

I. Introduction

In the last few decades there has been a shift in how robotic intelligence is understood [1], [2]. While control architectures, information processing, world representation, among others, are certainly important, the relevance of the morphology of the robot and its environment, as well as their mutual interactions has become apparent [3]. In fact, a new approach called Embodied Artificial Intelligence (EAI) [4], [5], which emphasizes the emergence of intelligence as an interaction between brain, morphology and the different environments the robot must operate in, has begun to take hold. This more open view of the emergence of intelligence has been extended to consider the fact that intelligent systems, and in particular robots, must be able to operate and carry out tasks in sequences of environments that are often unknown at design time. That is, we are confronting open-ended learning problems and in these settings, it is not feasible to directly program the robots or even know what skills they will need in order to achieve the goals we want them to achieve.

To address these issues, and unlike previous approaches, Developmental Robotics (DR) is based on the idea that robots can autonomously acquire an increasingly complex set of sensorimotor and mental capabilities. This should be achieved through the interaction between their body and brain in the different environments they face during their lifetime, in a similar way to how humans do it. Developmental Psychology (DP) constitutes the main source of inspiration for DR [6], which tries to apply the same principles to robots. Cangelosi defines this field as [7]:

"Developmental robotics is the interdisciplinary approach to the autonomous design of behavioral and cognitive capabilities in artificial agents that takes direct inspiration from the developmental principles and mechanisms observed in the natural cognitive systems of children"

Developmental robotics focuses on the acquisition of experience and motor skills that emerge and develop from infancy to adulthood. It is during infancy and childhood when the majority of changes at the physical and psychological levels take place in human beings. However, this does not imply that development cannot occur during adulthood. In fact, it does.

A survey of Cognitive Developmental Robotics (CDR) has been published by Asada et al. [8] focusing on infant development of higher cognitive functions, such as empathy or imitation. They provide a description of how these functions emerge during the infant development period and how they have been deployed in a robotic system, assuming an unchanging morphology for the robot during its lifetime. Lungarella et al. [9] provide another survey that analyzes the factors involved in a development process. Compared to Asada's survey, it does not focus on cognitive development and places more emphasis on a morphological perspective and how the interaction between the body and the environment affects development. However, although it contemplates an embodied perspective, it is an introductory survey that does not delve into examples of physical morphological changes.

In this overview, we want to concentrate on a point that was not really addressed in any depth in any of those surveys: the importance of morphology and, specially, how progressive changes in morphology during development can affect behavior learning. It is important to state here that the concurrent development of function and morphology has been identified as an important aspect of development for a long time [10]–[12]. However, in robotics, research on this topic has been limited due to the practical difficulties of growing artificial systems.

The area that addresses these issues is called morphological development (MD). Its relevance stems from the fact that development represents a continuous and harmonic change of both the physical and the functional properties of the system as a whole and not of its individual components separately. Unfortunately, there is no clearly established specification of its limits. The term "morphological development" refers to the changes in body shape, properties and capabilities occurring during development. From a general viewpoint, this could go from changes in the morphology of single neurons and neural connections to changes in sensor layout, body size, muscle strength etc. Different authors include within morphological development different processes, such as body growth, which is probably the most intuitive one [13], but also the development of the cognitive apparatus [14], motor development [15] and sensory development [16]. These processes, as many authors have pointed out, are interrelated and mutually influenced [17]–[19] and the inclusion of some of them within the field, such as the development of the cognitive apparatus, depends on the specific definition one uses for the "morphology" of the individual.

For clarity in the scope of this paper, we consider a core perspective to morphology and morphological development, which is taken primarily as the growth of the mechanical body components, along with the maturation of the sensory and actuation systems.

More precisely, within the scope of morphological development as addressed in this paper we include:

- Growth: physical changes of the body.
- Motor maturation: variations in the action possibilities of the individuals.
- Sensory maturation: modifications in the capabilities for acquiring data from the environment.

This implies that, even though they are also considered morphological development by some authors, we exclude:

- Neural and neural system development: development of the neural system through neurogenesis.
- Sporadic morphological changes due to accidents.
- Aging: morphological changes that involve a progressive deterioration of the physical capabilities of the individuals, leading to an adaptation of the cognitive system to try to cope with this deterioration.
- Social aspects of development: such as imitation or development guided by a caregiver.

A more formal definition of morphological development in robots and the scope we address is given in section V.

The objective of this paper is to provide an overview of this area, including its bio-psychological background and the most representative work from a robotics perspective. To this end, we have tried to put together and compare in an accessible manner, first, what we consider the main sources of inspiration for this area from a psychological, physiological and computational perspective. Secondly, we have compiled and reviewed the main contributions from the robotic literature on the mechanisms and possible influence of developmental changes in the morphology and the sensorimotor apparatus, over the skill acquisition capabilities of robots for a specific set of representative tasks.

In the field of morphological development for robotics, the main questions that are being addressed by most authors are: does morphological development facilitate or complicate learning? If so, how can morphological development be applied in robots to improve their learning performance when operating in open-ended settings?

As we will show in this review, these questions have only been partially answered and there are still many open issues that require attention. It is one of the objectives of this paper to highlight this and encourage researchers to look into them.

II. Open-ended learning, lifelong learning and Developmental robotics

Traditionally, in education, open-ended learning is taken as mediated by the particular intentions and purposes of the individual [20]. The individual defines what, when, and how it will learn depending on its goals and the needs arising from its interaction with the world and its own self-preservation [21].

Open-ended learning also implies that a robot or agent (a living or artificial entity endowed with a physical body and intelligence) is required to solve an unbounded sequence of tasks (or a task or tasks in an unbounded sequence of domains) that are not known beforehand. This implies that the way to solve them cannot be predefined at design time [22]. In other words, in this case the robot must display the capability of figuring out how to solve a task in a domain at run time.

Lifelong learning in robotics, on the other hand, addresses how to improve efficiency through the reuse and adaptation of previously learnt knowledge when dealing with a new domain or task within open-ended learning processes. It was Thrun and Mitchel [23] that postulated that lifelong learning should improve on simply handling each learning process independently. In this sense, lifelong learning can benefit from the principles and advances in developmental robotics [24].

The basic research assumption of developmental robotics [25], [26] as stated by [27], is that "true intelligence in natural and (possibly) artificial systems presupposes three crucial properties: embodiment of the system, situatedness in a physical or social environment, and a prolonged epigenetic developmental process through which increasingly more complex cognitive structures emerge in the system as a result of interactions with the physical or social environment".

However most of the research that has been carried out in this field has concentrated on the development of cognition [8], often including the cognitive apparatus (neurons, connections, etc.) within an otherwise fixed body. It has mostly ignored the development of the body of the robot as a complementary tool. Thus, most of the efforts have been devoted to the study of CDR [27], which seeks to design robotic systems through the application of insights gained from the ontogenetic development of the cognitive capabilities of living organisms.

To achieve this, developmental robotics Cognitive Architectures (CAs) use motivations, in particular intrinsic motivations, such as novelty, curiosity or competence acquisition, within open-ended learning to obtain primary cognitive capabilities [28]. Examples of this can be found in the most relevant CAs of the field, like the iCub CA [29], ERA [30], SASE [31] or HAMMER [32].

A core idea behind CDR is that the robot needs such primary capabilities in later developmental stages to fulfill operational (often called extrinsic) goals [33] like those provided by a human user or others acquired during life [7]. In fact, the developmental robotics field arose as a new perspective for obtaining real autonomous robots that can operate life-long, seeking goals whose source may be intrinsic or extrinsic usually with a close relationship to the developmental value system.

All this is fine, but, as indicated before, there is a missing piece in this whole approach and that is the fact that in most living beings it is not only the cognitive part of the system that changes throughout these developmental processes, but the bodies also undergo modifications during the lifetime of the system. Even though many these modifications probably emerged for reasons other than facilitating learning, they seem to provide an advantage to the individual in terms of its capabilities to learn in extremely complex open-ended settings. That is, evolution seems to have recruited these processes to facilitate learning in some circumstances.

Consequently, closer attention must be paid to how the body, that is, the morphology of the individual and its development, may affect its cognitive abilities. This will pave the way to studying how changes in morphology may lead to improving the capabilities of the individual to address life-long learning. It is important to note that this is a two-way street: the development of cognitive abilities can also influence the development of morphology [34]. However, from a robotics perspective, this is currently less relevant and in this paper we will just review research that addresses whether and how morphological development can be used to facilitate learning.

III. Why does morphology matter?

Traditionally it was thought that the body was not necessary for cognition. However, different studies have demonstrated that the body and environmental interaction are necessary to develop communicative and cognitive skills, among other traditional mental activities [35]–[37]. As argued by Lakoff and Núñez [38], a body is even required for functionalities such as mathematical thinking, something we often assume is a purely abstract mental process.

The importance of the body for artificial cognition in robotics started to become apparent in the 80s as an alternative to the limitations of the traditional symbolic AI systems [39], [40]. In this frame, Embodied Cognition (EC) [41], [42] emerged as a new paradigm that could overcome the limitations of the traditional mind-centered paradigm both in cognitive science and in AI. Wilson [43] explicitly highlighted the importance of the body and the sensory-motor apparatus for cognition, indicating, similarly to Lakoff and Núñez [44], that the body helps even in abstract mental activities.

Considering a body-based intelligence opens the question about what is and what can be considered a body, discussed under the field of Embodiment together with the how the body facilitates cognitive functions. In this line, there are different views and notion about what Embodiment is [45]–[48] and what it provides to cognition. However, it is not our aim to discuss here the notions of EC nor Embodiment. The idea of embodiment has been widely studied and developed by Pfeifer & Bongard [1], Brooks [49], Pfeifer & Iida [4], [50] and recently Hoffmann in [5] and [51]. In fact, Müller and Hoffmann [52] present three characteristics of the influence of morphology in robotics that are closely related to those described in this section: morphology simplifies control [53], facilitates perception [54] and performs computation [55], [56].

We refer the reader to the extensive literature on this topic [42], [45]. It provides a great case for the importance for cognition of the body interacting with the environment, [57], highlighting the relevance of grounding cognition in the sensorimotor information through body-environment interaction [58], [59]. The main conclusion is that a poorly chosen morphological design implies degraded performance and an increase in the complexity of the control structure when compared to a suitable one.

An example of morphology affecting control complexity can be found in the area of grasping systems. Most current grasping designs are based on the human hand, with its hardware and software complexities: large numbers of controllable joints, computational overhead, etc. However, Yokoi et al.[60], Odhner et al. [61] and Kontoudis et al. [62] have designed humanoid hands based on morphological principles, such as underactuated fingers and rough palms and fingers, that simplify robotic control. In fact, an extreme example of control simplification thanks to the physical design is the gripper developed by Brown and his team [63], [64]. Individual fingers are replaced by a single mass of a granular material that, when pressed onto a target object, flows around it and conforms to its shape. Although radical, this gripper greatly simplifies the physical design of the system and its control.

Another classical example is the domain of passive dynamic walkers [53], [65]. Their behavior emerges from the combination of the mechanical design and the characteristics of the environment, without any power supply or explicit controller. These walkers produce natural and efficient gaits when compared to most biped robots designs [66]–[68], whose motion is far from being as efficient as that of humans [69].

Summarizing, there seems to be a close relationship between the physical design of a robot and the complexity of its controller, as a function of the environment or environments and tasks to perform. This opens up a series of research questions of interest. One of the most relevant, addressed by many authors, such as [70]–[73], is how these relationships can be used to design more efficient robots and controllers.

However, a probably more interesting and subtle question, that has generated less attention, is whether this morphology-control relation or coupling can be used within a developmental process. That is, whether it can be used to improve the learning and adaptation capabilities of a robot that must address lifelong open-ended learning. In fact, it would be interesting to know whether this coupling provides any advantage when exploring complex behavioral spaces. If so, under what circumstances?

The following sections are structured as follows. Firstly, in section IV we will start from the human development perspective and review the work carried out by Piaget, Vygotsky, Thelen and Bernstein, whose studies about infant development and motor control constitute the biological and natural reference for most of the developmental robotics community. Secondly, section V provides a formal definition of morphological development and delimits the scope of this work. After that, section VI is devoted to the different strategies that can be used to apply morphological development, whilst section VII presents a review of the work carried out on morphological development in robots. This review will be mostly constrained to four paradigmatic motor control tasks, although some other examples will also be mentioned. Finally, section VIII provides a discussion on the state of the field, proposing lines of research we believe are open and promising.

IV. Developmental Psychology and Physiology

Developmental roboticists have paid a lot of attention to the field of developmental psychology, as it is during infancy when the human body as well as most cognitive aspects experience their major and most important changes.

It is during infancy when relations between sensory information and motor actions are established through the interaction among the different parts of the body and of these and the surrounding world. It is also during this stage when these relations start to build the cognitive representations of the world. In this sense, it was Piaget [74] who first studied the relationship between human cognitive development and physical maturation in depth.

A. Jean Piaget: Cognitive development

For Piaget, infant cognitive development consists in a progressive mental development and mental structural reorganization as a result of biological maturation and new discoveries about the world. He considers that knowledge is structured as a set of basic units called schemas, the simplest entities for cognitive representations of the world and for building structured knowledge. Schemas are consolidated through continuous adaptation to the world, which ocurrs in a repetitive process of assimilation-accommodation-equilibrium in order to always achieve a new equilibrium point [75].

Piaget organizes the sequence of infant and child cognitive development into four stages [76]:

1) Sensorimotor Stage (Stage 1, 0 - 2 years old).
2) Preoperational Stage (Stage 2, 2 - 7 years old).
3) Concrete Operational Stage (Stage 3, 7 - 11 years old).
4) Formal Operational Stage (Stage 4, 11+ years old).

These stages do not mean periods with clear temporal distinction. Furthermore, transitions between them are not due to abrupt changes, they are originated by the continuous development of the children themselves.

B. Lev Vygotsky: Social Interaction

For Piaget, development is self-centered and he considers that it emerges from the individual itself. A different perspective of development is provided by Vygotsky. He postulates that development is mainly influenced by the social interaction of the individual instead of through self-development. He structures cognitive development into Zones of Proximodistal Development (ZPD) that reflect the influence of the social interaction [77]. ZPD are defined as the "the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peers" [78]. Although he considers that work carried out by the learner "should be tied more closely to the level of potential development than to the level of actual development" [79] he also states that the level of actual development is achieved both from historical factors (what has been learnt previously) and from physical development (genetics).

C. Esther Thelen: Dynamical systems

Thelen centered her studies on infant motor abilities. She constructed her theory of infant development under the dynamical systems principle [80]. Although the idea of dynamical systems [81] is a general concept, not exclusive to any specific field, Thelen and Smith [82], [83] explain child development as the emergent product of the complex and dynamic interaction of many decentralized and local processes related to the child's growing body, brain and environment.

Two important aspects that influence human development can be highlighted in Thelen's dynamical system theory:

1) Multicausality. Biological systems are made up of many individual elements embedded and open to interactions in complex environments. These systems show coherent behavior: body parts are organized to produce some patterns without being programmed or having some specific information which says that things must be done in a specific way [84].
2) Nested timescales. Development happens at different time scales: from the long-term development of a specific behavior in motor control, to the here and now when the learning capability and environmental interaction are analyzed in the moment they happen. One of the best-known developmental psychology examples used by Thelen and Smith to demonstrate the combined effects of the concepts of multicausality and nested timescales is the highly studied A Not B

error [85],[86].

The use of a dynamical systems approach has significantly influenced developmental robotics research, as well as other fields of robotics and cognitive systems [87]–[89].

In addition to the importance of morphological development in the creation of cognitive structures in the individual, it is also important to point out how movement also influences cognitive development and learning capacity. This problem has been addressed by the Russian neurophysiologist N. Bernstein.

D. Nikolai Bernstein: Degrees of freedom problem

Unlike Piaget, Vygotsky and Thelen, who studied infant development, Bernstein's [90] studies analyze adult human motor development and the biomechanics of human movements in general. Bernstein's [91] most relevant theory was the formulation of the movement coordination problem as "the process of mastering redundant degrees of freedom". He defined coordination as "the organization of the control of the motor apparatus". He postulated that, in order to solve a new and unfamiliar motor problem, a reorganization of the control of an overwhelming number of degrees of freedom is required. The unmanageable number of degrees of freedom needs to be firstly reduced to a manageable number for solving the task.

An initial solution to the "Bernstein problem" is to freeze out a fraction of the degrees of freedom, by keeping the joint angles or the whole body rigidly or spastically fixed, allowing no or very little movement in the joints. Another reduction in degrees of freedom is accomplished by introducing temporarily strong, rigid couplings between multiple degrees of freedom, for example by moving two or more joint complexes in close phase relations. Following Bernstein's theory, improvement in skills would be achieved through a gradual release of the rigid control of the degrees of freedom and their incorporation into a dynamic, controllable system.

This theory was supported by Arutyunyan et al. [92], Vereijken [93], [94] and Newell [95] in pistol shooting, throwing, slalom like and writing examples respectively.

E. Common points

These studies share similarities among them. Bernstein considers the human body as a complex structure with muscles, bones, nerves, etc. Each motion implies a change in the interrelation among these elements in charge of movement, the nervous system and the brain [96]. Thelen's theory of dynamical systems and motor coordination is strongly influenced by Bernstein's work [97]. For Thelen, these changes are also observed in the modifications that happen during body maturation, with the consequent variations in the interrelationship between the physical body and the nervous system [98]. As the body grows and develops, the central nervous system must adapt to its new physiological characteristics to preserve motor control. Furthermore, researchers like Geert and van der Maas consider that the classical view of development by Piaget and Vygotsky can be included under the dynamical systems theory [99]–[101]. Thus, unifying the field of developmental science [102]–[105][106] under the umbrella of the dynamical systems theory: the Dynamic System Perspective (DSP) [104]. However, not all researchers in the developmental field agree [83], [107], leaving the discussion and the field open for future studies.

V. Morphological Development

A. What is morphological development?

In order to establish a clear notion of what is reviewed, we provide a formal definition of what we consider the morphology of a robot and what is morphological development in this paper.

For the purpose of this review, let a robot be a machine whose morphology is made up of a set of *l* links $L=\{l_1, l_2, \ldots, l_l\}$ a set of *j* joints $J=\{j_1, j_2, \ldots, j_j\}$, which can be actuated or not, and a set of *s* sensors $Ş=\{s_1, s_2, \ldots, s_s\}$ that runs during time $t \in [0, T]$, where t=0 is the beginning of its lifetime and t=T is the end. The robot has sets of *x*, *y* and *z* properties for the links (${}^{L}\mathrm{P}$), joints (${}^{J}\mathrm{P}$) and sensors (${}^{S}\mathrm{P}$) respectively, such that:

$$
{}^{L}\mathrm{P} = \begin{bmatrix} \mathrm{P}_{11} & \cdots & \mathrm{P}_{1l} \\ \vdots & \ddots & \vdots \\ \mathrm{P}_{x1} & \cdots & \mathrm{P}_{xl} \end{bmatrix}
$$

$$
{}^{J}\text{Ƥ} = \begin{bmatrix} \text{Ƥ}_{11} & \cdots & \text{Ƥ}_{1j} \\ \vdots & \ddots & \vdots \\ \text{Ƥ}_{y1} & \cdots & \text{Ƥ}_{yj} \end{bmatrix}
$$

$$
{}^{S}\text{Ƥ} = \begin{bmatrix} \text{Ƥ}_{11} & \cdots & \text{Ƥ}_{1s} \\ \vdots & \ddots & \vdots \\ \text{Ƥ}_{z1} & \cdots & \text{Ƥ}_{zs} \end{bmatrix}
$$

Therefore, the robot morphology can be defined as a set of these links, joints, sensors and their properties $\mathfrak{M} = \{\text{Ŀ}, J, \text{Ş}, {}^{\text{L}}\text{Ƥ}, {}^{J}\text{Ƥ}, {}^{S}\text{Ƥ}\}$. In this review we assume that the links, joints and sensors remain constant during the lifetime of the robot, that is, no new motors, links or sensors are created, while their properties can change. Thus, the morphology of the robot at the beginning and at the end of its lifetime can be specified by $\mathfrak{M}_{\boldsymbol{t=0}} = \{\text{Ŀ}, J, \text{Ş}, {}^{\text{L}}\text{Ƥ}_{\boldsymbol{t=0}}, {}^{J}\text{Ƥ}_{\boldsymbol{t=0}}, {}^{S}\text{Ƥ}_{\boldsymbol{t=0}}\}$ and $\mathfrak{M}_{\boldsymbol{t=T}} = \{\text{Ŀ}, J, \text{Ş}, {}^{\text{L}}\text{Ƥ}_{\boldsymbol{t=T}}, {}^{J}\text{Ƥ}_{\boldsymbol{t=T}}, {}^{S}\text{Ƥ}_{\boldsymbol{t=T}}\}$ respectively.

Under these assumptions, morphological development can be formally defined as a function *MD(t)* that describes the values of these properties in time for the lifetime of the robot:

$$
\{{}^{\text{L}}\text{Ƥ}, {}^{J}\text{Ƥ}, {}^{S}\text{Ƥ}\} = MD(t)\ \forall t \in [0, T]
$$

MD is generally a continuous function, as in the case of most natural systems, but it could also be discretized into stages. Although morphological development depends on several parameters, both intrinsic (genetic, etc.) and extrinsic (environment, social environment, etc.), from an analysis perspective this *MD* function describes the morphological development path that an individual has followed from birth and throughout its life. On the other hand, if the objective is to design *MD* functions, looking at the problem from a synthesis perspective, then dependencies on the appropriate variables must be explicitly included.

As postulated in section IV, morphological development can influence learning. Thus, the field is usually concerned with studying the influence on learning during the lifespan of an individual of different implementations of *MD(t)*. When different authors talk about growth, they are referring to physical changes of the body such as its size or mass which in this representation are properties of the links or, in the case of mass, also of the joints. The maturation of the sensor and joint/motor systems are usually closely related and linked to the physical growth of the body. On the one hand, joint/motor maturation implies an increment of the configuration possibilities of the individual and on the capabilities of the individual to actuate over the environment. It can be appreciated through changes in different properties, such as, for instance, muscle tone and strength, flexibility, etc. This allows, for instance, to increase the Range of Motion (ROM) available to the limbs or perform more precise movements.

Sensor maturation, on the other hand, is related to the development of the sensor system, usually improving its capabilities to acquire information from the environment. It allows perceiving the world in a more precise and reliable way, thanks to changes in the amount and quality of information obtained from it. Increases in visual and tactile resolution are examples of changes in parameters related to sensor maturation.

In practical terms, these changes in the properties of the different components of the robots have been implemented in robotics through different processes that are slight variations of those of natural systems, see section VI.

B. Morphological vs. brain development

From a mathematical and computational point of view, one way to facilitate searching for a solution in a complex search space is to initially consider a simplified version of the space and progressively add complexity as the algorithm is searching. In other words, for an artificial system, a progressive approach is applied in which at each point in time the algorithm is presented with a space that is slightly more complex, but also, and very importantly, with a starting point given by the best solution obtained up to that point.

Thus, seeking a solution for a task at an early stage means facing a simplified problem in which the set of available solutions is smaller [108], [109]. Reducing the number of possible solutions may mean that the best or optimal problem solution is not found among those available, but, assuming a certain level of continuity in the search space, we may reach a point that is closer to the final solution. As the complexification process progresses, the number of available solutions also increases, until the final stage, in which the solution search space of the global problem is reached. Initially simplifying the problem and reducing the number of available solutions is aimed at biasing and directing from the beginning the solutions towards the optimum in a more efficient way [110], [111].

An important difference between morphological development and cognitive development in the way they handle the learning process needs to be highlighted here. In cognitive development, the first units of knowledge to be learnt are basic features that will be used later to learn more complex knowledge nuggets compositionally. As an example, scaffolding learning [112] is used to learn basic behaviors such as walking in a straight line and steering and, later, other behaviors like avoiding obstacles are learnt by using the basic ones. This way of doing things usually leads to a perception of the processes as divided into stages. A first stage that produces the low-level controllers, a second stage where these are combined to achieve more complex behaviors and so on.

This is not the case for morphological development. The cognitive structures created at each point of the morphological development process are the starting point for subsequent learning. These starting structures are modified and adapted to the physical changes that occur during the morphological development process, giving rise to new cognitive systems better adapted to the new morphology and improving the effectiveness of the interaction with the environment.

Take, for instance, the case of a human learning to walk. Humans only remember how to walk with their current body. They have forgotten how to walk with shorter and weaker legs, as they did in the first steps of development, because the current controller is optimized for the current morphology. All of the previous controllers that were progressively adapted to the changing morphology were discarded as the morphology changed. Thus, it can be said that morphological development induces a learning path or curriculum for the controllers where the problem is simpler at the beginning and progressively becomes more complex. Humans learn to walk using a smaller body with a lower center of gravity, which favors finding stable configurations and reduces the potential damages of accidental falls, thus facilitating learning.

This idea that morphological variations guide the consolidation of previous behavior at the same time that they favor the emergence of new ones was addressed in robotics authors like Bongard [113], highlighting the concept that morphological development helps to simplify the incremental complexity of the subsequent task deploying simplified and less computational costly solutions.

C. Key features of morphological development

Traditionally in AI, searching for a suitable behavior to solve a task in a given domain for an embodied artificial agent implies two possible scenarios:

1) The morphology of the agent and the environment are fixed during the whole experiment.
2) The morphology of the agent is fixed, but the scenario is modified in terms of scaling it from a simple scenario to a more complex one.

The idea underlying the second approach is in fact the idea of curriculum learning. Humans learn faster and better when their training is well structured, organized and guided instead of random. Thus, simple and easy concepts are presented first, to facilitate the acquisition of new and more complex ones based on these [114]. There are several examples of this approach in the literature [115]–[117], proposing variations in the scenario for agents with fixed morphologies.

Physical changes open a new front for problem solving. It is not only the scenario that can be altered to scale problem difficulty, now the morphology can also be sequentially modified, offering a new range of possibilities to address the solution of the problems that arise. It is similar to creating a learning curriculum based on the development of the individual.

Bongard provides two examples of morphological variation in a variable and fixed environment. He first conducted a series of experiments in simulation with an anthropomorphic hand where both the morphology and the controller were evolved to meet one or more object manipulation objectives. Specifically, finding a controller to grasp between one to three objects in the environment [118]. Although this experiment does not involve morphological development, it represents the idea we want to transmit. He found that when there was only one object to grasp, it was irrelevant to evolve the morphology; evolving the controller sufficed to find a solution. However, when the number of objects increased in the scene, the combined evolution of the controller and the morphology led to an increase in performance, supporting the hypothesis that following a sequential and scalable process of evolution (in this case, both controller and morphology were scalable) the learning performance increases.

Afterwards, in [119] he presented a comparison among different morphological variations in a fixed environment. The task objective consists in reaching a source of light as fast as possible. In this case, those experiments that made use of morphological development to reach the target, performed better than those that did not, helping to discover faster successful locomotion behaviors. Savastano and Nolfi have also shown the importance of an incremental learning in their experiments with an iCub robot [120], [121]. These experiments will be discussed in detail in section VII.

On the other hand, morphological development can also be considered in the framework of affordance and schema variations. Although affordance [122] presents some nuances depending of the field where it is employed, it shares a similar meaning in all of them: The affordances of an object in relation to the observer are the action possibilities that the object has for the observer. It defines all of the possible interactions between the object and the observer that she can perceive.

In biology, physical changes afford new behaviors. Children start moving in the environment by crawling when they are too weak to walk. Once their body matures and becomes stronger, they change their posture from a 4 legged position to an upright position, modifying their behavior: instead of using 2 legs and 2 arms for moving, 2 legs are now enough and the arms take up a balancing function.

The same can be observed in robotics. In [123] we have an example of how different behaviors emerge thanks to variations in the morphology. In this case, the experiment consists in trying to find both a morphology and a behavior that adapts as well as possible to the task. The results show that, in addition to the fact that morphological changes favor the adaptation of the agent to the task, the behavior of the individual changes, leading to solutions that had not appeared using other morphologies.

Finally, even though they are not the focus this paper from a robotics perspective, it is important to note that development could also be extended to abrupt changes in the body schema representation [124], modifying this way the possible behaviors that are available to the individual. We would thus be re-describing the body and its capabilities for its control system. Iriki et al. [125] studied the integration of a tool within the body schema of monkeys. They found out that monkeys which actively use a rake for retrieve food, incorporate this tool within their peripersonal space and body schema. These modifications of body schema through tool use are also observed in human beings [126]–[128]. Another type of body schema imposed modification of behavior is the adaptation observed in patients who suffer the amputation of a limb [129], [130]. In the realm of robotics, this last type of abrupt variations in the morphology and their influence over the robot behavior have been addressed by A. Cully et al. [131]. Anyway, as indicated in the introduction we exclude these processes from the morphological development approaches considered in the following sections.

VI. Morphological development in robots

One important problem of MD research when applied to robotics is the fact that it is very difficult to design robots that implement some types of morphological changes easily. There are some experiments with real robots where morphology changes [132]. In them, the authors try to address the problems of deploying physical growing robots by building mobile extensible parts to simulate limb extensions. However, other variations, such as weight changes have not been considered in real systems. In the following subsections we provide a summary of the main strategies in order to address the problem of implementing MD in real robots.

A. Without hardware changes

The first strategy is to apply morphological development techniques that can be used without modifying the hardware of the robot. In this line, several authors have limited the Degrees Of Freedom (DOF) [133], [134], the ROM (which can be seen as a continuous approach to the liberation of DOF) [119], [135], [136] or the sensory information from the perceptual system of robots [120], [137]. Another approach is to use variable stiffness actuators in order to produce different behaviors by changing the stiffness of the joints, which can be controlled through software [138], [139].

While the fixed morphology approach is easy to implement, it does not allow growing the body except by building several robots with some variations in their parts. With the recent advances in 3D printing, this is a feasible approach that has been employed for the evolution of morphologies [140], [141], but to the best our knowledge only [142] has used it for proper morphological development.

However, there are other strategies that are better suited for growth: simulated morphological development or new materials and techniques to build robots.

B. Simulation

Regarding the simulation approach, the morphological development can be performed in a simulated environment where the robot starts with a smaller body and this body grows through time and while the robot learns a task [119], [136], [143]. The simulation will stop growing the robotic morphology as it reaches the same dimensions as the physical robot. Then, the robot controller obtained in simulation can be transferred to the physical robot. This strategy has been used in evolutionary robotics widely (the controller and/or the morphology are evolved in simulation and then transferred to the real robot) as real evaluations are resource and time expensive [144]. The disadvantage of this approach is that the simulation does not model all the physical properties and usually includes poorly modelled areas and simplifications. Therefore, the learning process could exploit these artifacts of the simulator and the controllers obtained could end up not performing well in the physical robot. This is called the reality gap. However, techniques developed in the evolutionary robotics field could be applied to overcome this problem [145], [146].

C. Novel mechanisms and materials

A third option to implement MD in real robots is building robots that are able to grow. If the robot is made of rigid materials, mechanisms can be used to extend the robotics limbs [147]–[149] or change the length between fixed points [150]. Other authors have used deformable materials that can be shaped through a custom machine, which allows them to reuse the same robot with several morphologies [151].

An interesting possibility is that of modular robots. Modular robots are small autonomous devices with connection faces that can be joined together to build larger robots. While most modular robots rely on manual connectors, some systems are able to change their morphology automatically. Self-reconfigurable modular robots have actuated connectors that allow them to add or release modules to/from their structures [152]–[155]. Other modular robots have passive connectors and rely on an external system to reconfigure them [156], [157].

Unlike rigid robots, there are robots that are made of flexible materials and therefore are able to expand and contract their bodies. The novel field related to these types of robots is called soft robotics. It has emerged as a new paradigm to build robots [158], [159]. Many robots in this field can expand and contract, but there also are some that can grow from the tip [160].

Most of these robots allowing morphological variations have not been used for MD and, to the best of our knowledge, only a few of them have been used to suggest that morphological variations may help obtain new behaviors [150], [161].

VII. Examples of application

After reviewing the main ideas underlying morphological development in general and morphological development in robots, we now want to focus on the work of different authors that studied the effects of morphological development on learning performance in different robotic applications. As most developmental robotics researchers have employed humanoid morphologies, the main subsection is based on anthropomorphic robots. However, we have found some related articles that use morphological development in other kinds of robotic morphologies and they are discussed at the end.

A. Humanoid morphology.

Most studies based on humanoid morphologies can be classified according to the task that was being addressed. In fact, most articles consider one of the three main motor tasks in human beings: reaching, grasping and walking, although there are some authors that also address the development of the vocal track. Therefore, this subsection is structured mainly around these four tasks. For each task, we will describe the main morphological developments on human beings, the biological theories behind them and how they have been applied to humanoid robots by robotic researchers.

1) *Reaching*

a) Natural reaching

Reaching behavior is observed in newborn infants [162], who start producing brief forward extensions of their hand-arm towards nearby objects after the primitive reflex phase. Several examples of this can be found in the literature: Von Hofsten [163], [164] reported an increase in object-oriented extensions of the hand in the first two months after birth. Fiorentino [165] and Shirley [166] mentioned that infants begin to reach using both arms. The arm movement and reaching behavior then appears to decline between seven and ten weeks. As pre-reaches become less frequent, infants spend increasingly more time visualizing the environment and fixating on the target. This happens in parallel to an improvement in the muscular tone of the neck and torso [167] at the same time infants start to focus their vision [168].

Reaching movements become more frequent again between weeks ten and thirteen. At this age, the tendency to open the hand during the movement phase also increases [169]. The study by Clifton [170], [171] gives an answer to an important question in terms of development: their conclusions state that proprioceptive feedback from the hand and arm are sufficiently well coordinated and precise so as not to require visual feedback for guiding the arm movement to the target.

Moreover, infants are able to store information about the location of the target and they can direct the hand toward the target [172] even when it is not possible to visualize it during the whole sequence of reaching. At the age of five months, infants will continue to reach toward an object even if it is darkened during the reaching sequence [173]. One important feature of infant reaching is that, the infants' reaching behavior becomes progressively straighter and smoother with age [174]. This pattern is due to the fact that infants begin reaching by holding the elbow relatively fixed, while moving the shoulder, which results in comparatively rounded or curved reaching trajectories [175]. During the second year, infants begin to coordinate elbow and shoulder rotation: they move both joints at the same time [176]. This is called the proximodistal behavior. This way of developing movement improves the learning speed, allowing for more controllable movements.

b) Robotic reaching

Developing reaching robots based on infant behavior helps to reveal and identify the underlying neural mechanisms behind motor development. Schlesinger, Parisi, and Langer [177] point towards Bernstein's DOF problem mentioned in section IV. They investigate the emergence of the reaching skill in a 2D space where they represent the arm (shoulder and elbow) and the visual field (body axis) of a robot, in a 3DOF system. The task consists in reaching an object placed at different positions. Neural networks are used as the controller of the 2D system. During the experiments, the strategy of freezing redundant joints (changes over the ${}^{J}\mathcal{P}$ matrix) emerges naturally and it is not programmed-in. With this solution, the shoulder follows the body rotation axis and only two joints need to be controlled, the body axis and the elbow joint. However, the authors only point out that freezing the redundant DOF arises spontaneously in the system. They do not address how, after being frozen, freeing emerges to offer all the movement possibilities of the system.

Other researchers base their studies on the infant development sequence and on its application to develop life-long learning robots. This is described by Law et al. [178] who also focus on the problem of coordinating visual input, arm postures and movements within a common spatial reference frame [135], [178]–[181], acting over the ${}^{J}\mathcal{P}$ and ${}^{S}\mathcal{P}$ matrices defined in section V. In [133], Lee et al. employ a robot system made up of an industrial robotic arm and a camera in order to reproduce the hand/eye system in infants. The task for this system consists in learning the effects and operational properties of its various motors and sensors, and then learn to control and coordinate them to achieve reaching behavior towards stimulating objects. That is, they also act over the ${}^{J}\mathcal{P}$ and ${}^{S}\mathcal{P}$ matrices. Specifically, morphological development is discretized into stages. The progression between successive stages of development occurs once a level of skills has been achieved in which the architecture no longer obtains new experiences. Their results show that the developmental approach is faster when compared to non-development and makes use of previous experience. Similar results and conclusion have been obtained in [137]. An incremental developmental sequence in the motor, sensor and brain system (changes over the ${}^{J}\mathcal{P}$ and ${}^{S}\mathcal{P}$ matrices) offers better performance when compared to the non-developmental approach. The transition from one stage to the next occurs when the task to be performed is mastered, similar to what was done in Lee's study.

Savastano and Nolfi [120], [121] have also studied infant development using an iCub robot [182] simulating the developmental sequence of reaching, through vision and neuro-motor development (changes over the ${}^{J}\mathcal{P}$ and ${}^{S}\mathcal{P}$ matrices), in a fourteen-DOF simulation of the iCub. The iCub is trained and tested in a manner that corresponds to the method used by Thelen [183] and von

Hofsten [163], in which the infant is supported in an upright position while a nearby object is presented within reach. Three main conclusions have been drawn from their results. The first one is that an incremental process of morphological development may offer better results with respect to a process that does not use it. The second is that the neuro-robotic model used to represent learning to reach does so in a similar way to how it is done in humans: the system learns by itself to lock the DOF that are further away from the center of the body (elbow) and mostly employs the closest ones (torso and shoulder). Finally, the third one corresponds to the observation that not every morphological development sequence is beneficial.

In a particular experiment, a progressive increase in visual ability did not produce a significant improvement in learning performance. In this case, motor development associated to a neural maturation of the control system (number of synapses connections and their plasticity) constituted the most relevant part in the developmental process. This seems to point towards the idea that although early constraints in robot development may help to improve task performance and learning, these constraints must be selected carefully because not all of them lead to the same results.

Similar conclusions were extracted in [184]. In this case, the task objective consisted in learning a specific inverse kinematic model of a 3DOF robotic arm, always following the same trajectory. The solution was reached in 5 different types of experiments, (the control experiment without development and the other 4 with development over the maximum range of movement of the arm and over the parameters of the proportional–integral–derivative, PID, controller (changes over the ${}^{J}\mathcal{P}$ matrix)). It was shown that in the same way that a suitable morphological development sequence may improve task performance, a not so suitable development sequence can be worse than no development. Obviously, this opens up two important points about morphological development applied to robots: the first one is that morphological development may be both beneficial and detrimental for learning a task. The second one, is that it is necessary to identify those conditions that make morphological development beneficial and understand these processes in order to deploy more efficient robots.

2) Grasping

a) Natural grasping

Grasping emerges in infants once some notions about reaching have been acquired. Although there is a time gap between reaching and the initialization of voluntary grasping (three or four months), the two behaviors overlap considerably. It seems that grasping is highly dependent on reaching [185].

Grasping behavior emerges during the first 4-12 months always following the same and predictable developmental pattern [186], characterized by the increasing involvement of the thumb in the grasping task with the consequent development from an imprecise task performance, to a more precise one. A second important point for the refinement of the grasping skill, is the adaptation of the hand to the shape of the object to grasp. This issue is called hand pre-shaping [187]. Hand pre-shaping is the orienting of the hand and fingers during the movement of the arm toward the target, configuring them for the final grasp action, independently of the size, shape, and position of the target object. This movement arises several weeks after the start of reaching and by nine months infants can correctly orient their hand toward the target once they have previewed it [188].

b) Robotic grasping

Although there are a large number of examples in the literature devoted to solving the problem of grasping in different kinds of hands, grippers, etc. we have found very few examples that address grasping from a developmental point of view and mostly in conjunction with other actions, such as reaching and visual recognition. Natale et al. [189], [190] address development in the sense of learning the association of motor babbling actions with hand tracking and object recognition, without the morphological changes we have defined in section V. Caligiore at al. [191] reference to the strategy of actuating over the joint properties (acting over the ${}^{J}\mathcal{P}$ matrix) of the robot by locking DOFs of the arm, to facilitate learning. However, that strategy is imposed by the researchers and the DOF is not unlocked during the experiment. Law et al. [181] address morphological variations over the sensor system, acting over the gazing mechanism, and motor system, acting over the robot arm (${}^{J}\mathcal{P}$ and ${}^{S}\mathcal{P}$ matrices) but there is not specific morphological development over the hand and grasping task.

However, there are examples of morphological variations similar to those we have presented in section V where only the hand and the grasping task are involved, but in other research fields. One is Bongard's example [118], which we have already mentioned, where a 3 fingered hand learns how to grasp through morphological variations (changes over the ${}^{L}\mathcal{P}$ matrix) in the

Evolutionary robotics field. The other is Deimel et al. [192] from the Automated Design field. In this case their study consists in the co-design of a 4 fingered soft hand for grasping where the morphological and control parameters are tested at the same time (changes over the ${}^{L}\mathcal{P}$ and ${}^{J}\mathcal{P}$ matrices).

3) Walking

a) Natural walking

Walking, like reaching, initially appears as a spontaneous reflex-like behavior in newborn infants [193]. Neonates produce a stepping reflex that is obtained by supporting the infant in an upright position, and then placing its feet on a horizontal surface [194]. Young infants produce stepping movements with their legs, but by the age of three months, these movements disappear.

Traditionally, it was assumed that the vanishing of the reflex behavior was due to brain maturation [195]. However, Thelen [196], [197] found that between ages two and nine months, when infants do not generate stepping movements on a stationary surface, they continue to produce the stepping pattern when placed on a moving treadmill or in a swimming pool. Thelen and Ulrich propose that the early stepping pattern does not disappear, however, this stepping movement is not enough for learning how to walk until new abilities emerge (postural control and body strength). From zero to three months, infants are first able to lift their heads, then their head and chest, and finally, their upper body while using their arms for support [198]. Between three and six months of age, they learn to roll over, and maintain a seated, upright posture. Between six and nine months of age, they are able to transition from the prone to a seated position on their own, and they can also pull themselves up to a standing position. At the age of ten months they are able to perform supported walking, whereas at eleven months they can stand alone without support. Finally, near their first birthday, most infants take their first steps.

Although early walking behavior is far from being an adult like behavior [199], infant walking improves though practice and development [200]–[202]. Also, the ability to dynamically balance while moving emerges during the second year. Early walkers tend to rely on stiff legs (freezing DOFs of the leg) which helps to preserve upright posture but fails to recruit available degrees of freedom in the legs and hips to perform a more natural and smooth movement. However, older infants free DOFs gradually, recruiting a high number of joints and performing smoother and more fluid movements. Indeed, the strategy of freezing and then freeing DOFs also plays a central role in motor-skill models.

b) Robotic walking

Although human like walking has been studied and deployed in legged robots [203]–[205], as in the case of grasping, there are few cases that involve morphological development.

Lungarella and Berthouze investigate the bouncing behavior produced by a 12 DOF humanoid robot suspended in a harness with springs [206], [207] and the same scenario but adding a nonlinear coupling between the environment and the robot [134], [208]. They analyze whether and how an initial reduction of the number of biomechanical degrees of freedom affect learning (changes over the ${}^{J}\mathcal{P}$ matrix). To this end, they propose three sets of experiments for each scenario, for only the 12DOF humanoid robot and for the 12DOF humanoid robot with the nonlinear coupling. The objective is to compare how development influences performance in a simple environment and in the same environment but with a nonlinear perturbation:

1) 1-DOF exploratory control: left and right hip servos are fed with identical motor commands. Other joints are stiff.
2) 2-DOF exploratory control: hip and knee joints are controlled by their own oscillator unit.
3) Bootstrapped 2-DOF exploratory control: the second degree of freedom is released and controlled once the system obtained in the 1-DOF configuration reaches the stationary regime.

In the environment without the nonlinear perturbation, they found that the bootstrapped 2-DOF control helps to stabilize the interplay between environment and neural dynamics, reducing the amplitude of oscillatory behaviors and contributing this way to the adaptability of the system during its lifetime [206], [207].

When the nonlinear perturbation is added during the learning process [134], [208], they do not observe any instance where the bootstrapped 2-DOF control leads to better performance over the task. On the contrary, the introduction of the second DOF yields poorer behaviors. However, they observed that a DOF freeing and freezing cycle helps to stabilize the system in the 2-DOF configuration: when the second DOF was added and the performance decreased, freezing the second DOF returned the system to the same behavior as in the 1-DOF experiment. With a subsequent release of the second DOF, the 1-DOF behavior was sustained. When an external perturbation acted over the 2-DOF system, it collapsed. With another cycle of freeing and freezing, the system recovered its stabilization. Although in the words of the researchers it is necessary to carry out more experiments, this behavior shows similarities to the one observed by Goldfield [209]: a large number of DOFs are difficult control, and a reduction simplifies the problem in order to find solutions. Releasing DOFs in a controlled manner allows reaching the solution to the unconstrained problem.

4) Vocal learning

a) Natural vocalization

Although it may not be intuitive, the vocal system is considered a part of the motor system: its activation, affects the environment and its surroundings.

Technologies like Magnetic Resonance Imaging (MRI) or X-rays have been very helpful to understand how vocal tract development goes from infancy to adulthood [210], [211]. For example, overall vocal track length for a male grows from 8 to 17cm [212] whilst the vocal fold length also increases from 4mm to 18mm and 12mm for an adult male and female respectively [213]. The growth of the vocal tract is not uniform, and the ratio of the pharynx length versus the length of the oral cavity varies from infancy to adulthood [211]. These differences in the size and shape of the vocal tract affect speech production with age [214], [215]. Furthermore, the various structures involved in speech production develop at different time steps. This different level of development has a direct impact over the sound produced, requiring a continuous learning and adaptation from the children to preserve and improve their speech generating abilities [216].

In addition to the development of the vocal tract, Davis and MacNeilage [217] and Moore and Ruark [218] have pointed at the importance of motor control for sound production, showing how motor control over lips and tongue in infants, influence the sounds produced.

b) Robotic vocalization

There are many examples in the literature that try to reproduce human vocalization in robotics [219], [220]. Concretely, examples where a human like vocal tract has been physically created to reproduce human speech in the same way as humans do it: using lips, vocal chords, etc. [221]–[223]. However, most of those examples are based on the physical design of an adult vocal tract and they do not address the influence of development.

This is also the case of the theories and mathematical models of the human vocal tract, most of them are based on the adult vocal tract [224], [225], but not all. Story et al. have created the first age-dependent mathematical model of the vocal tract [226] (changes over the ${}^{L}\mathcal{P}$ matrix*)*. The DIVA project [216] goes a step further by creating a computational model which addresses learning to generate speech sounds under a developmental approach. DIVA is a speech model which, according to its authors, "demonstrates that self-produced auditory feedback is sufficient to train a mapping between auditory target space and articulator space under conditions in which the structures of speech production undergo considerable developmental restructuring". It is based on the dimensions of the vocal tract included in Maeda's model [227] and development is simulated by altering those dimensions (changes over the ${}^{L}\mathcal{P}$ matrix*)*. The speech model is learnt by a Hebbian NN in which each training step starts with the weights obtained from the previous stage of morphological development of the vocal tract. In their review of the DIVA model, Tourville & Guenther give several examples were the model has shown "to be a valuable tool for studying the mechanisms underlying normal and disordered speech" [228] and highlighting its neurobiological background.

B. Nonhuman morphologies

Although the field of developmental robotics is mostly based on the human morphology, there are studies in with other morphologies where morphological development is studied in order to analyze how it modifies the learning rate of a robotic device. They share the main hypothesis of the area: morphological changes during knowledge acquisition may influence adaptation and learning rate.

Recently, Naya-Varela et al. [136] have compared how two different developmental mechanisms affect learning in a quadruped: growth of the limbs and extension of the ROM of those limbs (changes over ${}^{L}\mathcal{P}$ and ${}^{J}\mathcal{P}$ matrix). The task objective is locomotion over a flat surface. Morphological development through growth showed better performance for various growth rates, both compared to non-development and to the gradual increase of the ROM. On the other hand, the increase of the ROM does not show any advantage over no-development. Naya-Varela et al. also studied whether the advantage of morphological development through growth (changes over ${}^{L}\mathcal{P}$ matrix), was applicable to two other similar morphologies: a hexapod and an octopod [143]. Interestingly, growth only showed an advantage over non-development at one specific growth rate in the hexapod, while it showed no improvement in the octopod for any growth rate. The authors argue that morphological development improves learning performance when it is much harder to learn a task with the final developed morphology than using the initial non-developed one.

Up to this point, the examples we have mentioned under the umbrella of developmental robotics consider the lifespan of the individual. However, during morphological changes Bongard [119] considers two time scales, ontogenetic (lifespan of an individual) and phylogenetic (lifespan of a whole species). He compares the results of evolving a robot behavior considering morphological changes affecting the ${}^{L}\mathcal{P}$ and ${}^{J}\mathcal{P}$ matrices during ontogenetic time, phylogenetic time and both together as well as to a base control example where no morphological modifications are introduced. All of these for a quadruped and a hexapod robot. The target objective consisted in reaching a source of light as fast as possible. Each experiment contemplated 4 phases and each phase was associated to a specific state of the robots. The results show that considering an evolutionary process where the robot morphology changes between phases but remains constant in each phase performs worse than the base experiment (no morphological change in any phase) due to the abrupt changes that take place in the sensorimotor-relation at the beginning of each phase. Nevertheless, their results also show that changing the ontogenetic body plan during the evolutionary process in each phase contributes to faster success in learning the task. Furthermore, developing the morphology while learning the behavior has demonstrated a more robust performance under environmental perturbations.

As in the previous study by Bongard, Vujovic et al. [142] show the influence of performing morphological development during evolution instead of only evolution without morphological development. The aim of the study consists in comparing the results obtained after applying an evolutionary or an EvoDevo sequence over 3D printed real robots which need to walk over flat terrain. In order to do that, the length and thickness of the legs are modified (changes over the ${}^{L}\mathcal{P}$ matrix). The experiments offer similar results to the previous one. The combination of evolution and development yields an improvement of the fitness in the experiment. However, the authors show that a poorly chosen developmental system leads to poorer results than considering

TABLE I.
Morphological Development.

Anthropomorphous				
	Body part	**Principle of interest**	**Biological references**	**Robotic references**
Reaching	**Arm**	Pre-reaching movement.	Von Hofsten [163], [164]	Savastano & Nolfi [120], [121]
		Freeing and Freezing DOF. Limb constrains.	Bernstein [90]; Van Emmerik & Newell [94]; Arutyunyan, Gurfinkel & Mirskii [92]; Newell & van Emmerik [95]; McDonald, Van Emmerik & Newell, [93]; Berthier, Clifton, McCall & Robin [171]	Schlesinger, Parisi, & Langer [177]; Gomez, Lungarella & Eggenberger-Hotz [137]; Lee, Meng & Chao [133]; Ivanchenko & Jacobs [184]
	Hand - Eye	Self-discover. Sensorimotor coordination.	Mathew & Cook [162]; Von Hofsten [164]	Chao, Lee, & Lee [179]; Law, Shaw, & Lee [181]; Lee, Law, Shaw, & Sheldon [135]
Grasping	**Hand**	Babbling arm movement & grasping	Piaget [74]; Lee [37]; Corbetta & Santello [185]	Natale, Metta & Sandini [189]; Natale, Orabona, Metta, & Sandini [190]; Caligiore, Ferrauto, Parisi, Accornero, Capozza & Baldassarre [191];
		Adaptable grasping.	Erhardt [186]; Wren & Fisher [187]; McCarty, Clifton, Ashmead, Lee & Goubet [188]	**no-MD:** Bongard [118]; Deimel, Irmisch, Wall & Brock [192]
Walking	**Legs**	Walking.	Adolph, Vereijken & Shrout, [200]; Adolph & Avolio [201]; Okamoto, Okamoto & Andrew [202]; Vereijken & Adolph [199]	M. Lungarella & L. Berthouze [134], [206], [207]; L. Berthouze & M. Lungarella [208],
Vocal learning	**Vocal track**	Speech & sound production	Vorperian, Kent, Lindstrom, Kalina, Gentry, & Yandell [210]; Fitch & Giedd [211]; Xue & Hao [214]; Ménard, Schwartz & Boë [215]	Callan, Kent, Guenther & Vorperian [216]; Tourville & Guenther [228]; Story, Vorperian, Bunton & Durtschi [226]

Other Morphologies			
Morphological design	**Objective task**	**Developmental factor**	**Reference**
Hexapod	Phototaxis.	Leg extension and position	Bongard [119]
Square voxel design	Locomotion.	Physical properties (mass, weight, etc.) of each voxel	Kriegman, Cheney & Bongard [231]; Kriegman, Cheney, Corucci & Bongard [230]; Kriegman, Cheney, Corucci & Bongard [232]
Quadruped	Locomotion.	Leg thickness and length	Vujovic [142]
Bipedal	Locomotion.	Leg and head size	**no-MD:** Ha [123]
Quadruped, hexapod, octopod	Locomotion.	Leg extension and ROM	Naya-Varela, Faina & Duro [136], [143]

Table I. Summary of developmental applications: a) examples in anthropomorphous morphology and morphological variations b) in other kinds of physical designs and configurations. For the human morphology design, biological developmental examples are also presented.

only evolution. They attribute this to the fact that a search space reduction in the wrong direction eventually removes the good choices that development could have made at each stage.

Buckingham et al. [229] propose another approach to show how physical scaffolding leads to a faster adaptation to the environment. There is a variation in the morphology derived from the transition of the robotic agent from a low fidelity (lo-fi) to a high fidelity (hi-fi) simulator, changing the morphology from a less realistic, to a more realistic one, with changes in the wheel radius, motor gain, and wheel friction coefficient (changes in the $^{L}\mathcal{P}$ and $^{J}\mathcal{P}$ matrices). The task consists in solving a selective attention problem. The experiments compare the results obtained by agents whose controller is evolved first in the lo-fi simulator and then transferred to the hi-fi simulator. In this case, physical scaffolding improves performance only in sufficiently difficult tasks and considering enough time. This suggests a relation between the complexity of the behavior and the usefulness of scaffolding: if the task is too simple, evolution can find better solutions than with scaffolding. Moreover, as we have seen in [63], scaffolding can sometimes even be detrimental for the solution. As the task becomes more complex, the importance of scaffolding increases. Furthermore, in this case, scaffolding only provides an advantage when one parameter out of three (wheel friction) or all three parameters are considered in the experiment.

In a group of experiments by Kriegman et al. using a Voxel morphology with the task of achieving displacement through changes over $^{L}\mathcal{P}$, the authors showed not only that development improves performance over experiments without development [230], but also the resulting solutions offer a more robust and adaptable behavior when the environment changes [231], [232].

TABLE II

Development Strategies					
	R	G	W	VL	NH
$^{J}\mathcal{P}$	real&sim	sim	real		
$^{L}\mathcal{P}$		sim		sim	real&sim
$^{S}\mathcal{P}$					
$^{L}\mathcal{P}$ & $^{S}\mathcal{P}$					
$^{L}\mathcal{P}$ & $^{J}\mathcal{P}$		noMD: sim			sim
$^{J}\mathcal{P}$ & $^{S}\mathcal{P}$	real&sim	real			
$^{J}\mathcal{P}$ & $^{S}\mathcal{P}$ & $^{L}\mathcal{P}$					

Table II. Summary of the morphological development strategies presented in the examples of section VII: Reaching (R), Grasping (G), Walking (W), Vocal Learning (VL) and Non-Humanoid (NH) cases, versus the developmental strategies of section V. We label whether those examples are deployed over real robots or only in simulation (sim). We also indicate those examples that are not from the morphological development field.

In order to summarize all of these works, we provide a schematic representation in Table I. Each task of the table is related to its developmental biological references and to how it has been deployed in robotics. We decided to divide Table I into two parts. The first one, presents anthropomorphic examples of morphological development applied in robotics, with their corresponding biological references. The second part of the table is about morphological variations applied to a wide variety of morphologies, especially in simulation due to the difficulty of physically deploying some morphologies selected for those experiments, like the Voxel morphology.

VIII. Discussion and Conclusions

With the aim of organizing the information provided in the previous sections, Table II groups the studies on morphological development for different tasks presented in section VII according to the developmental strategies described in section V. It can be observed that variations in the parameters of the joints ($^{J}\mathcal{P}$) alone or in conjunction with other forms of development is the most prevalent developmental strategy. Freeing and freezing DOF or variation in the ROM of the joints are the main culprits in this strategy, probably due to their ease of implementation.

In terms of prevalence in the literature, this strategy is followed by variations in in the properties of the links ($^{L}\mathcal{P}$). This approach has been mainly addressed in simulation (with only one case over real robots [142]) due to the difficulty of deploying and working with physical robots.

Finally, sensor variation ($^{S}\mathcal{P}$) is the least represented developmental strategy. It always appears in conjunction with the development of the joints, especially in in the group of reaching or reaching-grasping tasks. It is remarkable that the combination of the three development strategies has not been addressed in the literature.

An important characteristic of the cases presented in Table II is the fact that they are examples where the influence of morphological development has constituted an advantage for learning a specific task or to achieve a goal. In addition, there are some studies which also show that applying morphological development does not improve the individual's ability to learn or adapt, but, in fact, may be detrimental. Those studies are presented in Table III, where we also include the hypotheses provided by the different authors about why the type of morphological development they selected for the experiments has not been successful or has been detrimental. However, these hypotheses are sometimes simple explanations and they do not go in any depth into the causes and implications.

Regarding Table III, Naya-Varela et. al show how, in the case of quadruped walking, an inappropriate extension of the ROM is irrelevant [136] and how a successful morphological development strategy for a specific morphology is also irrelevant for different, albeit similar ones [143]. In [119], a decrease of the performance is due to a drastic change in the sensory-motor relation. A similar result can be found in [206], where dramatic changes in the experiments lead to unstable situations in the system. In [120], [121], an improvement of visual acuity does not significantly affect the results compared to the non-developmental sequence case. In the case of Ivanchenko and Jacobs, they encounter the three situations [184]: development improves performance, it does not have an effect on performance and it decreases performance, in two kinds of experiments (when only the gain of the controller is developed and when development takes place in the reverse order, from the farthest joints to the nearest ones). This shows that not all development processes are adequate for all tasks. A similar conclusion was reached by Buckingham et al. [229] and Bongard [118]. In fact, they argue that morphological development makes sense when the problem presents a high enough level of complexity to apply development, if not, the non-developmental configuration is usually able to find a solution that is as good as the developmental one.

Thus, the authors´ hypotheses presented in Table III about why some of their MD experiments have not improved learning can be classified into three main categories: (1) the development process is not well aligned with the nature of the task. that is, another type of morphological development function would offer better results for the same task [136], [184]; (2) the problem is too simple and, therefore, development does not provide any advantage [118], [120], [121], [143], [229]; and (3) the development rate generates perturbations that negatively affect learning [119], [208]. However, these hypotheses still need to be confirmed.

So why does a specific morphological development process prove effective during human development and not always when applied to robots? The examples presented in Table III indicate that this question remains open and will require a more systematic approach to answer it. Nevertheless, the literature presented in this review, both biological and robotic, highlight the close relationship among three factors: morphology, environment and cognitive system. It is this relationship that influences the effectiveness of learning through a developmental sequence. In human beings, such a morphological development process has been shown to be effective because during natural evolution a biological curriculum based on morphological development was created that has allowed optimizing the learning sequence [74], [97]. Thus, evolution has adapted the learning mechanisms to the morphological changes the systems were undergoing, favoring rapid adaptation to the environment, and therefore, favoring survival. However, this is not the case in the robotic examples we have found in the literature and discussed in this article. The sequence of development, morphology and learning mechanism have been selected and established by the authors "ad-hoc" without any clear knowledge or guidelines on how this could influence learning. Consequently, this synergy has not been achieved and thus, a chosen development process may or may not be correctly aligned with the task and environment to favor learning.

TABLE III

Paper	Morphology	Objective task	Development Strategy	Analysis
Bongard[119]	Quadruped-Hexapod.	Phototaxis.	$^{L}\mathcal{P}$ & $^{J}\mathcal{P}$: - Leg angle amplitude. - Leg growth.	**Performance increases** over the non-developmental (ND) configuration if legs grow gradually and the leg angle amplitude also increases gradually. **Performance decreases** if these changes happen abruptly instead of gradually. **Hyp:** This lack of performance is arguably due to the drastic changes that take place in the controller.
Ivanchenko & Jacobs [184]	Three joint robotic arm.	Learning a given trajectory. Inverse kinematic problem.	$^{J}\mathcal{P}$: Gradually freeing DOFs. - Control development: - Gain development in control system.	**Performance increases** with a suitable combination of physical and control development over a ND process. **Performance decreases** over the ND process due to an unsuitable development sequence (e.g: inverse development: locking the proximal joints instead of the distal ones or simply gain development). **Hyp:** there is not a good match between the development process and the nature of the task.
Savastano & Nolfi[120], [121]	Humanoid Robot.	Reaching & Grasping.	$^{J}\mathcal{P}$ & $^{S}\mathcal{P}$: - Visual acuity. - Neural motor development.	**Performance increases** thanks to neural motor development simulating infant babbling and employing a mechanism of freezing DOFs. **Performance is** similar to ND in the case of visual development. **Hyp:** due to the experimental set up, and the sensory-motor architecture, the motor system has more relevance than the sensor system.
Buckingham[229]	4 Wheeled Robot.	Selective attention.	$^{L}\mathcal{P}$ & $^{J}\mathcal{P}$: - Simulation environment scaffolding.	**Performance increases** through scaffolding with only certain morphological and simulation parameters. **Performance is similar** to ND **or decreases** in other configurations. **Hyp:** if the problem has a simple solution, development does not provide an advantage over ND.
Lungarella & Berthouze[134], [208]	Humanoid Robot.	Swinging (oscillatory) behavior.	$^{J}\mathcal{P}$: - Freeing & Freezing DOFs.	**Performance is similar** to ND and robustness increases by following a sequence of freeing & freezing of DOFs. **Performance decreases** with one single liberation of the locked DOF**.** **Hyp:** one single liberation induces perturbations that make the oscillatory system collapse.
Bongard[118]	3, 4, 5 fingered hand.	Grasping and active perception.	Evolution. $^{L}\mathcal{P}$: - Phalange length. - Phalange radii. - Phalange space.	**Performance** and robustness **increase** under certain conditions, especially when the task grows in complexity. **Performance is equal** in simple tasks. **Hyp:** if the problem is simple, there is no difference between development and ND.
Naya-Varela, Faina & Duro [136]	Quadruped.	Displacement.	$^{L}\mathcal{P}$ & $^{J}\mathcal{P}$: - Leg growth. - Leg angle amplitude.	**Performance increases** with morphology growth **Performance is equal** when development involves variations in the ROM. **Hyp:** for this task and morphology, liberation of the ROM impedes optimal solutions until the final morphology. This does not happen with growth.
Naya-Varela, Faina, & Duro [143]	Quadruped, hexapod and octopod.	Displacement.	$^{L}\mathcal{P}$: - Leg growth.	**Performance increases** when learning to solve the task involves a certain level of complexity for the final morphology. **Performance is equal** when it is easy for the final morphology to solve the task. **Hyp:** if learning how to solve problem is easy for the grown individual, there is no difference between development and ND.

Table III. Summary of the main developmental application examples and morphological changes where it is explicitly stated that development has not been successful over non-development. In the analysis column, we briefly present the explanations given by the authors of the papers about the reasons why development improves or reduces performance, followed by their hypotheses (Hyp) about why morphological changes lead to poorer results in each case.

Four challenges are identified that still need to be researched in morphological development applied to robots: (1) Identify boundary conditions where morphological development provides an advantage over fixed morphologies. This could shed light on how to choose a cognitive architecture for a given morphology and environment and avoid those mechanisms that could affect development negatively. (2) Currently, most of the works have been focused on analyzing the effects of morphological development with a predetermined MD function, *MD(t)*, while other parameters could be considered, such as energy level. Therefore, a second challenge would be to design a methodology that allows us to produce an optimal morphological development trajectory in robots. This sequence would include the morphological parameters to change, the initial conditions and the pace of this variation over the lifetime of the robots. (3) Perform morphological development with regards to ^{L}P in real robots by using new mechanisms and materials. As we have seen, there is only one example in the literature that carries out ^{L}P

morphological development in a physical robot [142]. However, it involves constructing multiple slightly different versions of the robot, which is time consuming. New materials would open the possibility to design morphologies that are more susceptible to physical changes, simplifying the application of morphological development to real robots (see section VI.C.). (4) As most of the previous work has been carried out over humanoid morphologies or bio-inspired morphologies, a final challenge would be to generalize the previous methodology to structures that are not bio-inspired. Although biological inspired robots are characterized by their diverse and heterogeneous morphologies, we believe that all of them share common aspects, resulting from natural evolution, with regards to their susceptibility to MD. Thus, basic principles would need to be established that would allow new robotic structures to take advantage of morphological development.

Another research direction that we have not addressed is how learning can affect morphological development, which has been documented in humans [233], [234]. In robotics, the training while learning a task does not trigger any processes that change the morphology per se (e.g. the robots' muscles do not become stronger), but the learning could trigger the *MD* function. In fact, [133], [137], [235] have attempted to synthesize the development function based on the skill level, *MD(t, skill level)*. In addition to this, the ability to change morphological properties could also be used to improve the performance of recurrent tasks in which the robot specializes in after birth.

Summarizing, as we have seen, morphological development in humans is highly documented and numerous examples have been provided that show its usefulness and effectiveness for learning. However, the application of morphological development in robotics is still in its infancy and the different experiments that have been carried out have not always been equally effective. This opens up a very exciting research field that needs to be addressed in depth, both formally and empirically.

References

[1] R. Pfeifer and J. Bongard, *How the body shapes the way we think: a new view of intelligence*. MIT press, 2006.
[2] R. Pfeifer, "Dynamics, morphology, and materials in the emergence of cognition," in *Annual Conference on Artificial Intelligence*, 1999, pp. 27–44.
[3] R. Chrisley, "Embodied artificial intelligence," *Artif. Intell.*, vol. 149, no. 1, pp. 131–150, 2003.
[4] R. Pfeifer and F. Iida, "Embodied artificial intelligence: Trends and challenges," in *Embodied artificial intelligence*, Springer, 2004, pp. 1–26.
[5] M. Hoffmann and R. Pfeifer, "Robots as powerful allies for the study of embodied cognition from the bottom up," in *The Oxford Handbook of 4E Cognition*, 2018, pp. 840–862.
[6] M. Asada, K. F. MacDorman, H. Ishiguro, and Y. Kuniyoshi, "Cognitive developmental robotics as a new paradigm for the design of humanoid robots," *Rob. Auton. Syst.*, vol. 37, no. 2–3, pp. 185–193, 2001.
[7] A. Cangelosi and M. Schlesinger, *Developmental robotics: From babies to robots*. MIT Press, 2015.
[8] M. Asada *et al.*, "Cognitive Developmental Robotics: A Survey," *IEEE Trans. Auton. Ment. Dev.*, vol. 1, no. 1, pp. 12–34, 2009.
[9] M. Lungarella, G. Metta, R. Pfeifer, and G. Sandini, "Developmental robotics: a survey," *Conn. Sci.*, vol. 15, no. 4, pp. 151–190, 2003.
[10] D. W. Thompson and others, *On growth and form.* Cambridge Univ. Press, 1942.
[11] S. Kumar and P. J. Bentley, *On growth, form and computers*. Elsevier, 2003.
[12] J. Bongard and R. Pfeifer, "Evolving complete agents using artificial ontogeny," in *Morpho-functional Machines: The new species*, Springer, 2003, pp. 237–258.
[13] A. F. Roche, *Growth, maturation, and body composition: the Fels Longitudinal Study 1929-1991*. Cambridge University Press, 1992.
[14] M. Götz and W. B. Huttner, "The cell biology of neurogenesis," *Nat. Rev. Mol. cell Biol.*, vol. 6, no. 10, pp. 777–788, 2005.
[15] K. Williams, "What is motor development?," *Quest*, vol. 41, no. 3, pp. 179–182, 1989.
[16] E. J. Gibson, A. D. Pick, and others, *An ecological approach to perceptual learning and development*. Oxford University Press, USA, 2000.
[17] E. W. Bushnell and J. P. Boudreau, "Motor development and the mind: The potential role of motor abilities as a determinant of aspects of perceptual development," *Child Dev.*, vol. 64, no. 4, pp. 1005–1021, 1993.
[18] R. N. Aslin and L. B. Smith, "Perceptual development," *Annu. Rev. Psychol.*, vol. 39, no. 1, pp. 435–473, 1988.
[19] A. Diamond, "Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex," *Child Dev.*, vol. 71, no. 1, pp. 44–56, 2000.
[20] W.-M. Roth and A. Roychoudhury, "The development of science process skills in authentic contexts," *J. Res. Sci. Teach.*, vol. 30, no. 2, pp. 127–152, 1993.
[21] S. M. Land and M. J. Hannafin, "A conceptual framework for the development of theories-in-action with open-ended learning environments," *Educ. Technol. Res. Dev.*, vol. 44, no. 3, pp. 37–53, 1996.
[22] S. Doncieux *et al.*, "Open-Ended Learning: A Conceptual Framework Based on Representational Redescription," *Front. Neurorobot.*, vol. 12, 2018.
[23] S. Thrun and T. M. Mitchell, "Lifelong robot learning," *Rob. Auton. Syst.*, vol. 15, no. 1–2, pp. 25–46, 1995.

[24] J. Weng *et al.*, "Autonomous mental development by robots and animals," *Science (80-.).*, vol. 291, no. 5504, pp. 599–600, 2001.
[25] J. Weng and Y. Zhang, "Developmental Robots - A New Paradigm," vol. 94. Lund University Cognitive Studies, pp. 163–174, 2002.
[26] J. Weng, "Developmental robotics: Theory and experiments," *Int. J. Humanoid Robot.*, vol. 1, no. 02, pp. 199–236, 2004.
[27] J. Zlatev and C. Balkenius, "Introduction: Why epigenetic robotics?," *1st International Workshop on Epigenetic Robotics*, 2001.
[28] G. Baldassarre and M. Mirolli, "Intrinsically motivated learning systems: an overview," in *Intrinsically motivated learning in natural and artificial systems*, Springer, 2013, pp. 1–14.
[29] D. Vernon, C. Von Hofsten, and L. Fadiga, *A roadmap for cognitive development in humanoid robots*, vol. 11. Springer Science & Business Media, 2011.
[30] A. F. Morse, J. De Greeff, T. Belpeame, and A. Cangelosi, "Epigenetic robotics architecture (ERA)," *IEEE Trans. Auton. Ment. Dev.*, vol. 2, no. 4, pp. 325–339, 2010.
[31] J. Weng, "On developmental mental architectures," *Neurocomputing*, vol. 70, no. 13–15, pp. 2303–2323, 2007.
[32] Y. Demiris and A. Meltzoff, "The robot in the crib: A developmental analysis of imitation skills in infants and robots," *Infant Child Dev. An Int. J. Res. Pract.*, vol. 17, no. 1, pp. 43–53, 2008.
[33] G. Baldassarre, "What are intrinsic motivations? a biological perspective," in *2011 IEEE international conference on development and learning (ICDL)*, 2011, vol. 2, pp. 1–8.
[34] A. Castro-Caldas *et al.*, "Influence of learning to read and write on the morphology of the corpus callosum," *Eur. J. Neurol.*, vol. 6, no. 1, pp. 23–28, 1999.
[35] K. Weigmann, "Does intelligence require a body?: The growing discipline of embodied cognition suggests that to understand the world, we must experience the world," *EMBO Rep.*, vol. 13, no. 12, pp. 1066–1069, 2012.
[36] R. J. Sternberg, "The concept of intelligence and its role in lifelong learning and success," *Am. Psychol.*, vol. 52, no. 10, pp. 1030–1037, 1997.
[37] M. H. Lee, "Intrinsic Activitity: From motor babbling to play," *2011 IEEE Int. Conf. Dev. Learn. ICDL 2011*, 2011.
[38] G. Lakoff and R. E. Núñez, "Where mathematics comes from: How the embodied mind brings mathematics into being," *Basic Books*, 2000.
[39] N. E. Sharkey and T. Ziemke, "Life, Mind, and Robots: The Ins and Outs of Embodied Cognition," in *Hybrid Neural Systems*, 1998.
[40] Y. Kuniyoshi, "Fusing autonomy and sociality via embodied emergence and development of behaviour and cognition from fetal period," *Philos. Trans. R. Soc. B*, vol. 374, no. 1771, p. 20180031, 2019.
[41] L. Shapiro, *The Routledge handbook of embodied cognition*. Routledge, 2014.
[42] L. Shapiro, *Embodied cognition.* New York, NY, US: Routledge/Taylor & Francis Group, 2011.
[43] M. Wilson, "Six views of embodied cognition," *Psychon. Bull. Rev.*, vol. 9, no. 4, pp. 625–636, 2002.
[44] R. A. Wilson and L. Foglia, "Embodied Cognition," in *The Stanford Encyclopedia of Philosophy*, Spring 201., E. N. Zalta, Ed. Metaphysics Research Lab, Stanford University, 2017.
[45] R. Chrisley and T. Ziemke, "Embodiment," *Encycl. Cogn. Sci.*, pp. 1102–1108, 2002.
[46] T. Ziemke, "Disentangling notions of embodiment," in *Workshop on Developmental Embodied Cognition*, 2001, pp. 83–88.
[47] T. Ziemke, "Are robots embodied," in *First international workshop on epigenetic robotics Modeling Cognitive Development in Robotic Systems*, 2001, vol. 85, pp. 701–746.
[48] T. Ziemke, "What's that thing called embodiment?," in *Proceedings of the 25th Annual Conference of the Cognitive Science Society*, 2003, vol. 25, no. 25, pp. 1134–1139.
[49] R. A. Brooks, "Elephants Don't Play Chess," *Rob. Auton. Syst.*, vol. 6, pp. 3–15, 1990.
[50] R. Pfeifer, F. Iida, and G. Gómez, "Morphological computation for adaptive behavior and cognition," in *International Congress Series*, 2006, vol. 1291, pp. 22–29.
[51] M. Hoffmann and R. Pfeifer, "The implications of embodiment for behavior and cognition: animal and robotic case studies," in *The implications of Embodiment: Cognition and Communication.*, W. Tschacher and C. Bergomi, Eds. Exeter: Imprint Academic, 2012, pp. 31–58.
[52] V. C. Muller and M. Hoffmann, "What is morphological computation? On how the body contributes to cognition and control," *Artif. Life*, vol. 23, no. 1, pp. 1–24, 2017.
[53] S. H. Collins, M. Wisse, and A. Ruina, "A three-dimensional passive-dynamic walking robot with two legs and knees," *Int. J. Rob. Res.*, vol. 20, no. 7, pp. 607–615, 2001.
[54] D. Floreano *et al.*, "Miniature curved artificial compound eyes," *Proc. Natl. Acad. Sci.*, vol. 110, no. 23, pp. 9267–9272, 2013.
[55] L. Larger *et al.*, "Photonic information processing beyond Turing: an optoelectronic implementation of reservoir computing," *Opt. Express*, vol. 20, no. 3, pp. 3241–3249, 2012.
[56] E. A. Rückert and G. Neumann, "Stochastic optimal control methods for investigating the power of morphological computation," *Artif. Life*, vol. 19, no. 1, pp. 115–131, 2013.
[57] M. H. Bickhard, "Is embodiment necessary?," in *Handbook of Cognitive Science*, Elsevier, 2008, pp. 27–40.
[58] T. Froese and T. Ziemke, "Enactive artificial intelligence: Investigating the systemic organization of life and mind," *Artif. Intell.*, vol. 173, no. 3–4, pp. 466–500, 2009.
[59] R. Manzotti, "Embodied AI beyond Embodied Cognition and Enactivism," *Philosophies*, vol. 4, no. 3, p. 39, 2019.
[60] H. Yokoi, A. H. Arieta, R. Katoh, and W. Yu, "Mutual Adaptation in a Prosthetics Application," *Embodied Artif. Intell.*, pp. 146–159, 2004.
[61] L. U. Odhner *et al.*, "A compliant, underactuated hand for robust manipulation," *Int. J. Rob. Res.*, vol. 33, no. 5, pp. 736–752, 2014.
[62] G. P. Kontoudis, M. V Liarokapis, A. G. Zisimatos, C. I. Mavrogiannis, and K. J. Kyriakopoulos, "Open-source, anthropomorphic, underactuated robot hands with a selectively lockable differential mechanism: Towards affordable prostheses," in *2015 IEEE/RSJ*

International Conference on Intelligent Robots and Systems (IROS), 2015, pp. 5857–5862.

[63] E. Brown *et al.*, "Universal robotic gripper based on the jamming of granular material," *Proc. Natl. Acad. Sci.*, vol. 107, no. 44, pp. 18809–18814, 2010.

[64] J. Amend and H. Lipson, "The JamHand: Dexterous Manipulation with Minimal Actuation," *Soft Robot.*, vol. 4, no. 1, pp. 70–80, 2017.

[65] T. McGeer, "Passive dynamic walking," *I. J. Robot. Res.*, vol. 9, no. 2, pp. 62–82, 1990.

[66] J. Chestnutt, M. Lau, G. Cheung, J. Kuffner, J. Hodgins, and T. Kanade, "Footstep planning for the honda asimo humanoid," in *Proceedings of the 2005 IEEE international conference on robotics and automation*, 2005, pp. 629–634.

[67] C. Li, R. Lowe, and T. Ziemke, "Humanoids learning to walk: A natural CPG-actor-critic architecture," *Front. Neurorobot.*, vol. 7, no. APR, pp. 1–19, 2013.

[68] S. Feng, X. Xinjilefu, C. G. Atkeson, and J. Kim, "Optimization based controller design and implementation for the atlas robot in the darpa robotics challenge finals," in *2015 IEEE-RAS 15th International Conference on Humanoid Robots (Humanoids)*, 2015, pp. 1028–1035.

[69] J. Hurst, "Building robots that can go where we go," *IEEE Spectr.*, 2019.

[70] M. Matarić and D. Cliff, "Challenges in evolving controllers for physical robots," *Rob. Auton. Syst.*, vol. 19, no. 1, pp. 67–83, 1996.

[71] H. Lipson and J. B. Pollack, "Automatic design and manufacture of robotic lifeforms," *Nature*, vol. 406, no. 6799, pp. 974–978, Aug. 2000.

[72] N. Cheney, J. Bongard, and H. Lipson, "Evolving soft robots in tight spaces," in *Proceedings of the 2015 annual conference on Genetic and Evolutionary Computation*, 2015, pp. 935–942.

[73] V. Trianni, "Evolutionary robotics: model or design?," *Front. Robot. AI*, vol. 1, p. 13, 2014.

[74] J. Piaget and M. Cook, *The origins of intelligence in children*, vol. 8, no. 5. International Universities Press New York, 1952.

[75] J. Fleming, "Piaget and Cognitive Development," *PhD Master Thesis*, 2004.

[76] J. Piaget, "Part I: Cognitive development in children: Piaget development and learning," *J. Res. Sci. Teach.*, vol. 2, 1964.

[77] S. Chaiklin and others, "The zone of proximal development in Vygotsky's analysis of learning and instruction," *Vygotsky's Educ. theory Cult. Context*, vol. 1, pp. 39–64, 2003.

[78] L. S. Vygotsky, *Mind in society: The development of higher psychological processes*. Harvard university press, 1980.

[79] J. V Wertsch and P. Tulviste, "L.S. Vygotsky and contemporary developmental psychology.," *Dev. Psychol.*, vol. 28, no. 4, p. 548, 1992.

[80] E. Thelen, "Dynamic Systems Theory and the Complexity of Change," vol. 15, no. 2, pp. 255–283, 2005.

[81] R. D. Beer, "Dynamical approaches to cognitive science," *Trends in Cognitive Sciences*, vol. 4, no. 3. pp. 91–99, 2000.

[82] L. B. Smith and E. Thelen, "Development as a dynamic system," *Trends Cogn. Sci.*, vol. 7, no. 8, pp. 343–348, 2003.

[83] E. Thelen and L. B. Smith, "Dynamic Systems Theories," in *Handbook of Child Psychology. Vol.1. Theoretical models in human development*, W. D. y R. M. Lerner, Ed. New York, 1998, pp. 258–308.

[84] E. Thelen, B. D. Ulrich, and P. H. Wolff, "Hidden skills: A dynamic systems analysis of treadmill stepping during the first year," *Monogr. Soc. Res. child Dev.*, pp. 1–103, 1991.

[85] E. Thelen, "Time-scale dynamics and the development of an embodied cognition," in *Mind as Motion: Explorations in the Dynamics of Cognition*, R. Port and T. van Gelder, Eds. Cambridge MA: MIT Press, 1995, pp. 69–100.

[86] E. Thelen, G. Schöner, C. Scheier, and L. B. Smith, "The dynamics of embodiment: A field theory of infant perseverative reaching," *Behav. Brain Sci.*, vol. 24, no. 1, pp. 1–34, 2001.

[87] S. Nolfi, D. Floreano, and D. D. Floreano, *Evolutionary robotics: The biology, intelligence, and technology of self-organizing machines*. A Bradford book: MIT Press, 2000.

[88] H. Mori and Y. Kuniyoshi, "A human fetus development simulation: Self-organization of behaviors through tactile sensation," *2010 IEEE 9th Int. Conf. Dev. Learn. ICDL-2010 - Conf. Progr.*, pp. 82–87, 2010.

[89] A. Morse, T. Belpaeme, A. Cangelosi, and C. Floccia, "Modeling U shaped performance curves in ongoing development," in *Proceedings of the Annual Meeting of the Cognitive Science Society*, 2011, vol. 33, no. 33.

[90] N. Bernstein, *The co-ordination and regulation of movements*. London: Pergamon Press, 1966.

[91] R. Bongaardt and O. G. Meijer, "Bernstein's theory of movement behavior: Historical development and contemporary relevance," *J. Mot. Behav.*, vol. 32, no. 1, pp. 57–71, 2000.

[92] G. A. Arutyunyan, V. S. Gurfinkel, and M. L. Mirskii, "Investigation of aiming at a target," *Biophysics (Oxf).*, vol. 13, no. 3, pp. 642–645, 1968.

[93] P. V McDonald, R. E. A. Van Emmerik, and K. M. Newell, "The effects of practice on limb kinematics in a throwing task," *J. Mot. Behav.*, vol. 21, no. 3, pp. 245–264, 1989.

[94] B. Vereijken, R. E. A. Emmerik, H. T. A. Whiting, and K. M. Newell, "Free(z)ing degrees of freedom in skill acquisition," *J. Mot. Behav.*, vol. 24, no. 1, pp. 133–142, 1992.

[95] K. M. Newell and R. E. A. Van Emmerik, "The acquisition of coordination: preliminary analysis of learning to write," *Hum. Mov. Sci.*, vol. 8, no. 1, pp. 17–32, 1989.

[96] H. T. A. Whiting, *Human motor actions: Bernstein reassessed*. Elsevier, 1983.

[97] E. Thelen, "Motor development as foundation and future of developmental psychology," *Int. J. Behav. Dev.*, vol. 24, no. 4, pp. 385–397, 2000.

[98] E. Thelen, "Bernstein's legacy for motor development: How infants learn to reach," *Prog. Mot. Control*, vol. 1, pp. 267–288, 1998.

[99] P. Van Geert and H. Steenbeek, "Explaining after by before: Basic aspects of a dynamic systems approach to the study of development," *Dev. Rev.*, vol. 25, no. 3, pp. 408–442, 2005.

[100] P. Van Geert, "Vygotskian dynamics of development," *Hum. Dev.*, vol. 37, no. 6, pp. 346–365, 1994.

[101] H. L. J. Van Der Maas and B. Hopkins, "Developmental transitions: So what's new?," *Br. J. Dev. Psychol.*, vol. 16, no. 1, pp. 1–13,

1998.
[102] P. Van Geert, “The dynamics of general developmental mechanisms: From Piaget and Vygotsky to dynamic systems models,” *Curr. Dir. Psychol. Sci.*, vol. 9, no. 2, pp. 64–68, 2000.
[103] H. L. J. Der Maas and others, “Beyond the metaphor?,” *Cogn. Dev.*, vol. 10, pp. 621–642, 1995.
[104] D. C. Witherington, “The dynamic systems approach as metatheory for developmental psychology,” *Hum. Dev.*, vol. 50, no. 2–3, pp. 127–153, 2007.
[105] P. Van Geert, “We almost had a great future behind us: The contribution of non-linear dynamics to developmental-science-in-the-making.,” *Dev. Sci.*, vol. 1, no. 1, pp. 143–159, 1998.
[106] R. M. Lerner, *Developmental science, developmental systems, and contemporary theories of human development*, vol. 1. Wiley Online Library, 2007.
[107] E. Thelen and E. Bates, “Connectionism and dynamic systems: Are they really different?,” *Dev. Sci.*, vol. 6, no. 4, pp. 378–391, 2003.
[108] J. L. Elman, “Learning and development in neural networks: The importance of starting small,” *Cognition*, vol. 48, no. 1, pp. 71–99, 1993.
[109] G. Turkewitz and P. A. Kenny, “Limitations on input as a basis for neural organization and perceptual development: A preliminary theoretical statement,” *Dev. Psychobiol. J. Int. Soc. Dev. Psychobiol.*, vol. 15, no. 4, pp. 357–368, 1982.
[110] E. L. Newport, “Maturational constraints on language learning,” *Cogn. Sci.*, vol. 14, no. 1, pp. 11–28, 1990.
[111] C. M. Conway, M. R. Ellefson, and M. H. Christiansen, “When less is less and when less is more: Starting small with staged input,” in *Proceedings of the Annual Meeting of the Cognitive Science Society*, 2003, vol. 25, no. 25.
[112] J. Saunders, C. L. Nehaniv, and K. Dautenhahn, “Teaching robots by moulding behavior and scaffolding the environment,” in *Proceedings of the 1st ACM SIGCHI/SIGART conference on Human-robot interaction*, 2006, pp. 118–125.
[113] J. Bongard, “Why morphology matters,” *horizons Evol. Robot.*, vol. 6, pp. 125–152, 2014.
[114] Y. Bengio, J. Louradour, R. Collobert, and J. Weston, “Curriculum learning,” in *Proceedings of the 26th annual international conference on machine learning*, 2009, pp. 41–48.
[115] S. Cabi, S. G. Colmenarejo, M. W. Hoffmann, M. Denil, Z. Wang, and N. Freitas, “The Intentional Unintentional Agent: Learning to Solve Many Continuous Control Tasks Simultaneously,” in *Proceedings of the 1st Annual Conference on Robot Learning*, 2017, vol. 78, pp. 207–216.
[116] C. Florensa, D. Held, X. Geng, and P. Abbeel, “Automatic goal generation for reinforcement learning agents,” in *35th International conference on machine learning*, 2018, pp. 1515–1528.
[117] C. Colas, P. Fournier, M. Chetouani, O. Sigaud, and P.-Y. Oudeyer, “CURIOUS: intrinsically motivated modular multi-goal reinforcement learning,” in *36th International conference on machine learning*, 2019, pp. 1331–1340.
[118] J. Bongard, “The utility of evolving simulated robot morphology increases with task complexity for object manipulation,” *Artif. Life*, vol. 16, no. 3, pp. 201–223, 2010.
[119] J. Bongard, “Morphological change in machines accelerates the evolution of robust behavior,” *Proc. Natl. Acad. Sci.*, vol. 108, no. 4, pp. 1234–1239, 2011.
[120] P. Savastano and S. Nolfi, “Incremental learning in a 14 DOF simulated iCub robot: Modeling infant reach/grasp development,” *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 7375 LNAI, pp. 250–261, 2012.
[121] P. Savastano and S. Nolfi, “A robotic model of reaching and grasping development,” *IEEE Trans. Auton. Ment. Dev.*, vol. 5, no. 4, pp. 326–336, 2013.
[122] L. Jamone *et al.*, “Affordances in psychology, neuroscience, and robotics: A survey,” *IEEE Trans. Cogn. Dev. Syst.*, vol. 10, no. 1, pp. 4–25, 2018.
[123] D. Ha, “Reinforcement Learning for Improving Agent Design,” *Artif. Life*, vol. 25, no. 4, pp. 352–365, 2019.
[124] M. Hoffmann, H. Marques, A. Arieta, H. Sumioka, M. Lungarella, and R. Pfeifer, “Body schema in robotics: a review,” *IEEE Trans. Auton. Ment. Dev.*, vol. 2, no. 4, pp. 304–324, 2010.
[125] A. Iriki, M. Tanaka, and Y. Iwamura, “Coding of modified body schema during tool use by macaque postcentral neurones.,” *Neuroreport*, vol. 7, no. 14, pp. 2325–2330, 1996.
[126] A. Maravita, C. Spence, and J. Driver, “Multisensory integration and the body schema: close to hand and within reach,” *Curr. Biol.*, vol. 13, no. 13, pp. 531–539, 2003.
[127] S. H. Johnson-Frey, “What’s so special about human tool use?,” *Neuron*, vol. 39, no. 2, pp. 201–204, 2003.
[128] A. Berti and F. Frassinetti, “When far becomes near: Remapping of space by tool use,” *J. Cogn. Neurosci.*, vol. 12, no. 3, pp. 415–420, 2000.
[129] A. Mayer, K. Kudar, K. Bretz, and J. Tihanyi, “Body schema and body awareness of amputees,” *Prosthet. Orthot. Int.*, vol. 32, no. 3, pp. 363–382, 2008.
[130] P. R. Bromage and R. Melzack, “Phantom limbs and the body schema,” *Can. Anaesth. Soc. J.*, vol. 21, no. 3, pp. 267–274, 1974.
[131] A. Cully, J. Clune, D. Tarapore, and J. B. Mouret, “Robots that can adapt like animals,” *Nature*, vol. 521, no. 7553, pp. 503–507, 2015.
[132] H. Hauser and F. Corucci, “Morphosis-Taking Morphological Computation to the Next Level,” in *Soft Robotics: Trends, Applications and Challenges*, 2017, pp. 117–122.
[133] M. H. Lee, Qinggang Meng, and Fei Chao, “Staged competence learning in developmental robotics,” *Adapt. Behav.*, vol. 15, no. 3, pp. 241–255, 2007.
[134] M. Lungarella and L. Berthouze, “Adaptivity via alternate freeing and freezing of degrees of freedom,” *ICONIP 2002 - Proc. 9th Int. Conf. Neural Inf. Process. Comput. Intell. E-Age*, vol. 1, pp. 482–487, 2002.
[135] M. Lee, J. Law, P. Shaw, and M. Sheldon, “An infant inspired model of reaching for a humanoid robot,” *2012 IEEE Int. Conf. Dev. Learn. Epigenetic Robot. ICDL 2012*, pp. 1–6, 2012.

[136] M. Naya-Varela, A. Faina, and R. J. Duro, “An Experiment in Morphological Development for Learning ANN Based Controllers,” in *IEEE World Congress on Computational Intelligence (WCCI)*, 2020.
[137] G. Gomez, M. Lungarella, and P. Eggenberger-Hotz, “Simulating development in a real robot: on the concurrent increase of sensory, motor, and neural complexity,” in *Proceedings of the 4th International Workshop on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems*, 2004, pp. 119–122.
[138] H. Q. Vu, H. Hauser, D. Leach, and R. Pfeifer, “A variable stiffness mechanism for improving energy efficiency of a planar single-legged hopping robot,” in *16th International Conference on Advanced Robotics (ICAR)*, 2013, pp. 1–7.
[139] H. V. Quy, L. Aryananda, F. I. Sheikh, F. Casanova, and R. Pfeifer, “A novel mechanism for varying stiffness via changing transmission angle,” in *IEEE International Conference on Robotics and Automation*, 2011, pp. 5076–5081.
[140] M. F. Hale *et al.*, “The ARE Robot Fabricator: How to (Re) produce Robots that Can Evolve in the Real World,” in *Artificial Life Conference Proceedings*, 2019, pp. 95–102.
[141] J. Auerbach *et al.*, “Robogen: Robot generation through artificial evolution,” in *Artificial Life Conference Proceedings 14*, 2014, pp. 136–137.
[142] V. Vujovic, A. Rosendo, L. Brodbeck, and F. Iida, “Evolutionary developmental robotics: Improving morphology and control of physical robots,” *Artif. Life*, vol. 23, no. 2, pp. 169–185, 2017.
[143] M. Naya-Varela, A. Faina, and R. J. Duro, “Some Experiments on the influence of Problem Hardness in Morphological Development based Learning of Neural Controllers,” in *Hybrid Artificial Intelligent Systems. HAIS 2020. Lecture Notes in Computer Science*, 2020, pp. 362–373.
[144] F. Mondada and D. Floreano, “Evolution and mobile autonomous robotics,” in *Towards Evolvable Hardware*, Springer, 1996, pp. 221–249.
[145] N. Jakobi, “Evolutionary robotics and the radical envelope-of-noise hypothesis,” *Adapt. Behav.*, vol. 6, no. 2, pp. 325–368, 1997.
[146] S. Koos, J.-B. Mouret, and S. Doncieux, “The transferability approach: Crossing the reality gap in evolutionary robotics,” *IEEE Trans. Evol. Comput.*, vol. 17, no. 1, pp. 122–145, 2013.
[147] S. Nansai, N. Rojas, M. R. Elara, and R. Sosa, “Exploration of adaptive gait patterns with a reconfigurable linkage mechanism,” in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2013, pp. 4661–4668.
[148] J. K. Sheba, E. Martínez-García, M. R. Elara, and L. Tan-Phuc, “Design and evaluation of reconfigurable Klann mechanism based four legged walking robot,” in *2015 10th International Conference on Information, Communications and Signal Processing (ICICS)*, 2015, pp. 1–5.
[149] T. F. Nygaard, C. P. Martin, E. Samuelsen, J. Torresen, and K. Glette, “Real-world evolution adapts robot morphology and control to hardware limitations,” in *Proceedings of the Genetic and Evolutionary Computation Conference*, 2018, pp. 125–132.
[150] H. Vu Quy *et al.*, “Gait versatility through morphological changes in a new quadruped robot,” in *5th International Symposium on Adaptive Motion of Animals and Machines (AMAM2011)*, 2011.
[151] D. Cellucci, R. MacCurdy, H. Lipson, and S. Risi, “1D printing of recyclable robots,” *IEEE Robot. Autom. Lett.*, vol. 2, no. 4, pp. 1964–1971, 2017.
[152] V. Zykov, E. Mytilinaios, B. Adams, and H. Lipson, “Self-reproducing machines,” *Nature*, vol. 435, no. 7039, pp. 163–164, 2005.
[153] M. Yim *et al.*, “Modular Self-Reconfigurable Robot Systems [Grand Challenges of Robotics],” *IEEE Robot. Autom. Mag.*, vol. 14, no. 1, pp. 43–52, 2007.
[154] K. Stoy, D. Brandt, D. J. Christensen, and D. Brandt, *Self-reconfigurable robots: an introduction*. MIT press Cambridge, 2010.
[155] A. Spinos, D. Carroll, T. Kientz, and M. Yim, “Variable topology truss: Design and analysis,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2017, pp. 2717–2722.
[156] L. Brodbeck, S. Hauser, and F. Iida, “Morphological evolution of physical robots through model-free phenotype development,” *PLoS One*, vol. 10, no. 6, p. e0128444, 2015.
[157] R. Moreno *et al.*, “Automated reconfiguration of modular robots using robot manipulators,” in *IEEE Symposium Series on Computational Intelligence (SSCI)*, 2018, pp. 884–891.
[158] D. Rus and M. T. Tolley, “Design, fabrication and control of soft robots,” *Nature*, vol. 521, no. 7553, pp. 467–475, 2015.
[159] C. Lee *et al.*, “Soft robot review,” *Int. J. Control. Autom. Syst.*, vol. 15, no. 1, pp. 3–15, 2017.
[160] E. W. Hawkes, L. H. Blumenschein, J. D. Greer, and A. M. Okamura, “A soft robot that navigates its environment through growth,” *Sci. Robot.*, vol. 2, no. 8, p. eaan3028, 2017.
[161] F. Corucci, M. Calisti, H. Hauser, and C. Laschi, “Novelty-based evolutionary design of morphing underwater robots,” in *Proceedings of the 2015 annual conference on Genetic and Evolutionary Computation*, 2015, pp. 145–152.
[162] A. Mathew and M. Cook, “The control of reaching movements by young infants,” *Child Dev.*, vol. 61, no. 4, pp. 1238–1257, 1990.
[163] C. Von Hofsten, “Developmental changes in the organization of prereaching movements,” *Dev. Psychol.*, vol. 20, no. 3, pp. 378–388, 1984.
[164] C. Von Hofsten, “Eye-hand coordination in the newborn,” *Dev. Psychol.*, vol. 18, no. 3, pp. 450–461, 1982.
[165] M. R. Fiorentino, “A basis for sensorimotor develop- ment, normal and abnormal: The influence of primitive, pos- tural reflexes on the development and distribution of tone,” *Springfield, IL:*, 1981.
[166] M. M. Shirley, *The first two years – a study of twenty- five babies*. Minneapolis: University of Minnesota Press, 1933.
[167] R. Griffiths, *The abilities of babies: a study in mental measurement*. University of London Press, 1986.
[168] M. D. Sheridan, A. Sharma, and M. Frost, *From birth to five years: children's developmental progress*. Routledge, 2002.
[169] B. L. White, P. Castle, and R. Held, “Observations on the development of visually-directed reaching,” *Child Dev.*, 1964.
[170] R. K. Clifton, D. W. Muir, D. H. Ashmead, and M. G. Clarkson, “Is visually guided reaching in early infancy a myth?,” *Child Dev.*, vol. 64, no. 4, pp. 1099–1110, 1993.

[171] N. E. Berthier, R. K. Clifton, D. D. McCall, and D. J. Robin, “Proximodistal structure of early reaching in human infants,” *Exp. brain Res.*, vol. 127, no. 3, pp. 259–269, 1999.
[172] D. H. Ashmead, M. E. McCarty, L. S. Lucas, and M. C. Belvedere, “Visual guidance in infants’ reaching toward suddenly displaced targets,” *Child Dev.*, vol. 64, no. 4, pp. 1111–1127, 1993.
[173] M. E. McCarty and D. H. Ashmead, “Visual control of reaching and grasping in infants,” *Dev. Psychol.*, vol. 35, no. 3, pp. 620–631, 1999.
[174] N. E. Berthier and R. Keen, “Development of reaching in infancy,” *Exp. brain Res.*, vol. 169, no. 4, pp. 507–518, 2006.
[175] N. E. Berthier, “Learning to reach: A mathematical model,” *Dev. Psychol.*, vol. 32, no. 5, pp. 811–823, 1996.
[176] J. Konczak and J. Dichgans, “The development toward stereotypic arm kinematics during reaching in the first 3 years of life,” *Exp. brain Res.*, vol. 117, no. 2, pp. 346–354, 1997.
[177] M. Schlesinger, D. Parisi, and J. Langer, “Learning to reach by constraining the movement search space,” *Dev. Sci.*, vol. 3, no. 1, pp. 67–80, 2000.
[178] J. Law, M. Lee, M. Hülse, and A. Tomassetti, “The infant development timeline and its application to robot shaping,” *Adapt. Behav.*, vol. 19, no. 5, pp. 335–358, 2011.
[179] F. Chao, M. H. Lee, and J. J. Lee, “A developmental algorithm for ocular-motor coordination,” *Rob. Auton. Syst.*, vol. 58, no. 3, pp. 239–248, 2010.
[180] M. Hüelse, S. McBride, J. Law, and M. Lee, “Integration of active vision and reaching from a developmental robotics perspective,” *IEEE Trans. Auton. Ment. Dev.*, vol. 2, no. 4, pp. 355–367, 2010.
[181] J. Law, P. Shaw, M. Lee, and M. Sheldon, “From saccades to grasping: A model of coordinated reaching through simulated development on a humanoid robot,” *IEEE Trans. Auton. Ment. Dev.*, vol. 6, no. 2, pp. 93–109, 2014.
[182] G. Metta, G. Sandini, D. Vernon, L. Natale, and F. Nori, “The iCub humanoid robot: an open platform for research in embodied cognition,” in *Proceedings of the 8th Workshop on Performance Metrics for Intelligent Systems*, 2008, pp. 50–56.
[183] J. P. Spencer and E. Thelen, “Spatially specific changes in infants’ muscle coactivity as they learn to reach,” *Infancy*, vol. 1, no. 3, pp. 275–302, 2000.
[184] V. Ivanchenko and R. A. Jacobs, “A developmental approach aids motor learning,” *Neural Comput.*, vol. 15, no. 9, pp. 2051–2065, 2003.
[185] D. Corbetta and M. Santello, *Reach-to-grasp Behavior: Brain, Behavior, and Modelling Across the Life Span*. Routledge, 2018.
[186] R. P. Erhardt, *Developmental Hand Dysfunction: Theory, Assessment, and Treatment*. Tuscon: Therapy Skill Builders, 1994.
[187] D. Wren and R. B. Fisher, “Dextrous hand grasping strategies using preshapes and digit trajectories,” in *1995 IEEE International Conference on Systems, Man and Cybernetics. Intelligent Systems for the 21st Century*, 1995, vol. 1, pp. 910–915.
[188] M. E. McCarty, R. K. Clifton, D. H. Ashmead, P. Lee, and N. Goubet, “How infants use vision for grasping objects,” *Child Dev.*, vol. 72, no. 4, pp. 973–987, 2001.
[189] L. Natale, G. Metta, and G. Sandini, “A developmental approach to grasping,” in *Developmental robotics AAAI spring symposium*, 2005, vol. 44.
[190] L. Natale, F. Orabona, G. Metta, and G. Sandini, “Exploring the world through grasping: a developmental approach,” in *2005 International Symposium on Computational Intelligence in Robotics and Automation*, 2005, pp. 559–565.
[191] D. Caligiore, T. Ferrauto, D. Parisi, N. Accornero, M. Capozza, and G. Baldassarre, “Using motor babbling and Hebb rules for modeling the development of reaching with obstacles and grasping,” *Int. Conf. Cogn. Syst.*, pp. E1–8, 2008.
[192] R. Deimel, P. Irmisch, V. Wall, and O. Brock, “Automated co-design of soft hand morphology and control strategy for grasping,” in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2017, pp. 1213–1218.
[193] E. Thelen and D. M. Fisher, “The organization of spontaneous leg movements in newborn infants,” *J. Mot. Behav.*, vol. 15, no. 4, pp. 353–372, 1983.
[194] P. R. Zelazo, N. A. Zelazo, and S. Kolb, “‘Walking’ in the Newborn,” *Science (80-.).*, vol. 176, no. 4032, pp. 314–315, 1972.
[195] M. B. McGraw, “Development of neuro-muscular mechanisms as reflected in the crawling and creeping behavior of the human infant,” *Pedagog. Semin. J. Genet. Psychol.*, vol. 58, no. 1, pp. 83–111, 1941.
[196] E. Thelen, B. D. Ulrich, and D. Niles, “Bilateral Coordination in Human Infants: Stepping on a Split-Belt Treadmill,” *J. Exp. Psychol. Hum. Percept. Perform.*, vol. 13, no. 3, pp. 405–410, 1987.
[197] E. Thelen, “Treadmill-elicited stepping in seven-month-old infants,” *Child Dev.*, vol. 57, no. 6, pp. 1498–1506, 1986.
[198] C. P. Johnson and P. A. Blasco, “Infant Growth and Development,” *Pediatr. Rev.*, vol. 18, no. 7, pp. 224–242, 1997.
[199] B. Vereijken and K. Adolph, “Transitions in development of locomotion,” in *Non-linear analyses of developmental processes*, G. J. P. Savelsbergh, H. L. J. van der Maas, and P. C. L. van Geert, Eds. Elsevier, 1999, pp. 137–149.
[200] K. E. Adolph, B. Vereijken, and P. E. Shrout, “What Changes in Infant Walking and Why,” *Child Dev.*, vol. 74, no. 2, pp. 475–497, 2003.
[201] K. E. Adolph and A. M. Avolio, “Walking infants adapt locomotion to changing body dimensions,” *J. Exp. Psychol. Hum. Percept. Perform.*, vol. 26, no. 3, pp. 1148–1166, 2000.
[202] T. Okamoto, K. Okamoto, and P. D. Andrew, “Electromyographic developmental changes in one individual from newborn stepping to mature walking,” *Gait Posture*, vol. 17, no. 1, pp. 18–27, 2003.
[203] Z. Lu, S. Lallee, V. Tikhanoff, and P. F. Dominey, “Bent Leg Walking Gait Design for Humanoid Robotic Child-iCub Based on Key State Switching Control,” *IEEE Symp. Robot. Appl.*, pp. 992–998, 2012.
[204] G. Taga, “Nonlinear dynamics of human locomotion: from real-time adaptation to development,” *Adapt. Motion Anim. Mach.*, pp. 189–204, 2006.
[205] S. Kuindersma *et al.*, “Optimization-based locomotion planning, estimation, and control design for the atlas humanoid robot,” *Auton. Robots*, vol. 40, no. 3, pp. 429–455, 2016.

[206] M. Lungarella and L. Berthouze, "On the Interplay Between Morphological, Neural, and Environmental Dynamics: A Robotic Case Study," *Adapt. Behav.*, vol. 10, no. 3, pp. 223–241, 2002.

[207] M. Lungarella and L. Berthouze, "Adaptivity through physical immaturity," in *Proceedings of the 2nd International Workshop on Epigenetics Robotics*, 2002, pp. 79–86.

[208] L. Berthouze and M. Lungarella, "Motor skill acquisition under environmental perturbations: On the necessity of alternate freezing and freeing of degrees of freedom," *Adapt. Behav.*, vol. 12, no. 1, pp. 47–64, 2004.

[209] E. C. Goldfield, *Emergent forms: Origins and early development of human action and perception*. Oxford University Press on Demand, 1995.

[210] H. K. Vorperian, R. D. Kent, M. J. Lindstrom, C. M. Kalina, L. R. Gentry, and B. S. Yandell, "Development of vocal tract length during early childhood: A magnetic resonance imaging study," *J. Acoust. Soc. Am.*, vol. 117, no. 1, pp. 338–350, 2005.

[211] W. T. Fitch and J. Giedd, "Morphology and development of the human vocal tract: A study using magnetic resonance imaging," *J. Acoust. Soc. Am.*, vol. 106, no. 3, pp. 1511–1522, 1999.

[212] U. G. Goldstein, "An articulatory model for the vocal tract of growing children, Doctor of Science thesis," MIT, Cambridge, Massachusett, 1980.

[213] I. R. Titze, "Physiologic and acoustic differences between male and female voices," *J. Acoust. Soc. Am.*, vol. 85, no. 4, pp. 1699–1707, 1989.

[214] S. A. Xue and G. J. Hao, "Changes in the human vocal tract due to aging and the acoustic correlates of speech production," *J. Speech, Lang. Hear. Res.*, vol. 46, no. 3, pp. 689–701, 2003.

[215] L. Ménard, J.-L. Schwartz, and L.-J. Boë, "Role of vocal tract morphology in speech development," *J. Speech, Lang. Hear. Res.*, vol. 47, no. 5, pp. 1059–1080, 2004.

[216] D. E. Callan, R. D. Kent, F. H. Guenther, and H. K. Vorperian, "An auditory-feedback-based neural network model of speech production that is robust to developmental changes in the size and shape of the articulatory system," *J. speech, Lang. Hear. Res.*, vol. 43, no. 3, pp. 721–736, 2000.

[217] B. L. Davis and P. F. MacNeilage, "The articulatory basis of babbling," *J. Speech, Lang. Hear. Res.*, vol. 38, no. 6, pp. 1199–1211, 1995.

[218] C. A. Moore and J. L. Ruark, "Does speech emerge from earlier appearing oral motor behaviors?," *J. Speech, Lang. Hear. Res.*, vol. 39, no. 5, pp. 1034–1047, 1996.

[219] J. Hornstein and J. Santos-Victor, "A unified approach to speech production and recognition based on articulatory motor representations," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2007, pp. 3442–3447.

[220] V. Tikhanoff, A. Cangelosi, and G. Metta, "Integration of speech and action in humanoid robots: iCub simulation experiments," *IEEE Trans. Auton. Ment. Dev.*, vol. 3, no. 1, pp. 17–29, 2010.

[221] R. Hofe and R. K. Moore, "Towards an investigation of speech energetics using 'AnTon': an animatronic model of a human tongue and vocal tract," *Conn. Sci.*, vol. 20, no. 4, pp. 319–336, 2008.

[222] K. Fukui *et al.*, "Development of a talking robot with vocal cords and lips having human-like biological structures," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2005, pp. 2023–2028.

[223] M. Nakamura and H. Sawada, "Talking robot and the analysis of autonomous voice acquisition," in *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2006, pp. 4684–4689.

[224] B. H. Story and I. R. Titze, "Parameterization of vocal tract area functions by empirical orthogonal modes," *J. Phon.*, vol. 26, no. 3, pp. 223–260, 1998.

[225] H. Takemoto, K. Honda, S. Masaki, Y. Shimada, and I. Fujimoto, "Measurement of temporal changes in vocal tract area function from 3D cine-MRI data," *J. Acoust. Soc. Am.*, vol. 119, no. 2, pp. 1037–1049, 2006.

[226] B. H. Story, H. K. Vorperian, K. Bunton, and R. B. Durtschi, "An age-dependent vocal tract model for males and females based on anatomic measurements," *J. Acoust. Soc. Am.*, vol. 143, no. 5, pp. 3079–3102, 2018.

[227] S. Maeda, "Compensatory Articulation During Speech: Evidence from the Analysis and Synthesis of Vocal-Tract Shapes Using an Articulatory Model," in *Speech Production and Speech Modelling*, W. J. Hardcastle and A. Marchal, Eds. Dordrecht: Springer Netherlands, 1990, pp. 131–149.

[228] J. A. Tourville and F. H. Guenther, "The DIVA model: A neural theory of speech acquisition and production," *Lang. Cogn. Process.*, vol. 26, no. 7, pp. 952–981, 2011.

[229] D. Buckingham and J. Bongard, "Physical scaffolding accelerates the evolution of robot behavior," *Artif. Life*, vol. 23, no. 3, pp. 351–373, 2017.

[230] S. Kriegman, N. Cheney, F. Corucci, and J. Bongard, "A minimal developmental model can increase evolvability in soft robots," in *Proceedings of the Genetic and Evolutionary Computation Conference*, 2017, pp. 131–138.

[231] S. Kriegman, N. Cheney, and J. Bongard, "How morphological development can guide evolution," *Sci. Rep.*, vol. 8, no. 1, pp. 1–17, 2018.

[232] S. Kriegman, F. Corucci, N. Cheney, and J. Bongard, "Interoceptive robustness through environment-mediated morphological development," in *GECCO 2018 - Proceedings of the 2018 Genetic and Evolutionary Computation Conference*, 2018, pp. 109–116.

[233] G. Schlaug, A. Norton, K. Overy, E. Winner, and others, "Effects of music training on the child's brain and cognitive development," *Ann. York Acad. Sci.*, vol. 1060, pp. 219–230, 2005.

[234] G. Vicente-Rodríguez, "How does Exercise Affect Bone Development during Growth?," *Sport. Med.*, vol. 36, no. 7, pp. 561–569, 2006.

[235] P.-Y. Oudeyer, A. Baranes, and F. Kaplan, "Intrinsically motivated learning of real-world sensorimotor skills with developmental constraints," in *Intrinsically Motivated Learning in Natural and Artificial Systems*, G. Baldassarre and M. Mirolli, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 303–365.