Towards Computational Developmental Model based on Synthetic Approaches

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***Abstract*—Cognitive developmental robotics (CDR) [1] has been tackling the issue of how human cognitive functions develop by means of a synthetic approach that developmentally constructs cognitive functions. "Physical embodiment" is the core idea of CDR, and is revisited to make its role clearer, that is, to enable information structuring through interactions with the environment, including other agents. This paper attempts to reveal the developmental process of human cognitive function from a viewpoint of synthetic approach towards building a computational developmental model for the process with brief introductions of existing CDR approaches.**

I. INTRODUCTION

One of the greatest challenges in trying to make artificial systems more intelligent is the acquisition of cognitive functions through learning and development since existing systems are of limited capability even in fixed environments. Related disciplines are not simply AI and robotics but also neuroscience, cognitive science, developmental psychology, sociology, and so on, and we share this challenge. An obvious fact is that we have too poor and little knowledge and too superficial implementations based on such knowledge to declare that we have only one unique solution to the mystery. The main reason is that there is little knowledge and few facts on the mechanism of human cognitive functions, therefore, the artificial systems that aim at realizing such functions are based on the designers' shallow understanding of them. A more serious issue is how these functions are learned and/or developed from a viewpoint of design. Therefore, we need to verify the current understanding and realization of the primary functions is sufficient or not if we suppose that the higher order cognitive functions are acquired through the development process from these primary functions?

One possibility to answer these claims and questions is to discuss how cognitive functions are acquired involving the context and dynamics of the whole system instead of separately realizing each cognitive function as a single module. A promising approach is a synthetic one based on both the explanation theory and more importantly the design theory that is expected to fill in the gap between the existing disciplines instead of staying in one closed discipline, and to provide new understanding of human cognitive development.

A representative synthetic approach is cognitive developmental robotics (in short, CDR) [1]. Similar approaches can be found in [2] or [3], but CDR puts more emphasis on the human/humanoid cognitive development. A slightly different approach is taken by ATR team [4] who aims to program humanoid behavior through the observation and understanding of human behavior and vice versa. Though partially sharing the purpose of human understanding, they do not exactly deal with developmental aspect.

First, we revisit "physical embodiment" and give a brief overview of the various aspects of infant development. Next, we introduce the model of development toward the exploration for the design principle of cognitive development. The model starts from the emergence of fetal movements, then motor skill development and body representation/spatial perception, and development of social behaviors. Next, we argue the key issues to understand and realize the higher order cognitive functions. Finally, future issues are given.

II. REVISITING "PHYSICAL EMBODIMENT"

The meaning of physical embodiment has been frequently defined and argued already (ex.,[5], [6], [7], [8], [1], [2], [9]). Kuniyoshi et al. [10], [11] described as follows:

> The agent's physical body specifies the constraints on the interaction between the agent and its environment that generate the rich contents of its process or consequences. It also gives the meaningful structure to the interaction with environment, and is the physical infrastructure to form the cognition and action.

The key concept of the above "physical embodiment" is shaped in the context of development as follows. At the early stage of human development (embryo, fetus, neonate, infant, and so on), interactions with various physical environments have a major role in determining the information structuring inside the individual such as body representation, motor image, and object permanency. On the other hand, at the later stage, social behaviors such as early communication, joint attention, imitation of various actions including vocalization, empathy, and verbal communication gradually emerged due to interactions with other agents. Regardless of the premature or mature

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state of the individual, the common aspect of these developmental processes is a sort of "scaffolding" by the environment including other agents that triggers the sensorimotor mapping and promotes the infants' autonomy, adaptability, and sociality, directly or indirectly, and explicitly or implicitly.

A. *Body and motion*

The fundamental body structure that generates the motions of animals, including humans, is the musculoskeletal system that traditionally corresponds to joint-link structure in robotics. The big difference between animals and robots is the type of actuator used in the system. The former uses the muscle structure while the latter uses the electromagnetic motors that are the most popular since they are easy to control and therefore applied to many products. Separating the target and the method of control, the electromagnetic motors can generate various kinds of motions such as low speed starting with high torque and continuous driving with low torque by choosing the method and tuning its control parameters. However, the traditional robot architecture meets with great difficulty in generating dynamic motions with touch while the former can realize instantaneous motions such as jumping, landing, punching, kicking, and throwing based on the efficient use of musculoskeletal body.

In the musculoskeletal structure, multiple muscles can be attached to a single joint and vice versa, that is, one muscle can be expanded across multiple joints, and these structures form the complex system [12]. Therefore, independent control of each joint is difficult, and the whole body movement is generated through the interaction with the environment. At a glance, it seems inconvenient, but this can be a solution to the problem of DoF freezing for robots with many DoFs pointed out by Bernstein as a fundamental issue of the motor development [13].

McKibben pneumatic actuators have been receiving increased attention as biomimetic artificial muscles to generate dynamic motions with compliance like natural muscles of animals (see Niiyama and Kuniyoshi [14], Hosoda et al. [15], and Takuma et al., [16]).

B. *Brain and sensory organs*

Information processing in the brain was included in the previous section from a viewpoint of motor control of the body. The motor control from spinal reflex system to higher order motor control involves the prefrontal cortex for planning and prediction, the basal ganglia and the cerebellum for motor coordination and regulation. Brain structure and its functions have been great mysteries, and neuroscience has been mainly focusing on micro structures and their functions, therefore understanding of the brain as a whole system including the body has not been investigated so much.

Even for the peripheral systems such as sensor and motor ones that seem well understood compared with the higher order cognitive functions, the sensor system as input and the motor one as output have been often separately attacked. However, the interpretation of the visual information often needs the motor information as shown in the kitten experiment by Held and Hein [17]. In the recent view, the role of locomotor experience on visual proprioception in 8-month-old infants was investigated to show that locomotor experience plays a causal role in the ontogeny of visual proprioception [18].

Another extreme case is the so called "sight unseen" phenomenon [19], where the subject who was supposed blind could walk along tails in the mountain or grasp objects without being able to "see them." Vision, in general, consists of two pathways, that is, "where" vision on the dorsal pathway and "what" vision on the ventral pathway [20], and these are combined to construct the normal vision. However, due to some accidents or disorders, some patients have a lesion on the latter pathway, and therefore cannot "see" the objects as a whole even though they can perceive the edges or lines (the primal vision information processing). In spite of this, the parietal area, the destination of the dorsal pathway, is normal and able to generate actions by connecting the fragmentary visual information with the corresponding motor commands. Thus, sensory and motor systems are strongly connected in the various kinds of forms.

Body representations have been called the "body schema," an unconscious neural map in which multi-modal sensory data are unified, and "body image," an explicit mental representation of the body and its functions [21]. Sometimes, it is called "motor image," that suggests a strong connection with motions. Ramachandran's famous book tells us how our brains are easily tricked by controlling the timing of motions such as synchronous rubbing of the noses to emerge the perception of nose extension [22]. This implies that motions deeply participate in the developmental process of sense and perception.

C. *Mind development through interactions*

From a viewpoint of synthetic approach, mind development is nothing but the modeling process of interaction between two agents. Different from collective behaviors such as a school of fish, it is the interaction between individuals supposing the identification of others or including its learning process. The development of the self from ecological self to interpersonal self, and further conceptual self, and temporally extended self [23] crucially depends on the relationship with others. This makes it difficult for current brain science to approach the issue since it is mainly based on the reductionism of higher cognitive functions into the regions in one individual's brain.

The mind is supposed to emerge from the interaction between two agents each of which has its own subjective view, and dynamic interaction between them forms an inter-subjective view shared by both [24]. It is neither subjective nor objective, which implies the importance of the communication that makes endless effort not simply to fill in the gap between two subjective views but more importantly to change them into something shared by both. The earliest form is the communication between infants and caregivers, starting from sensorimotor development to verbal communication through physical interaction such a holding, joint attention, (vowel) imitation, non-verbal communication, and so on. It is essential to build a computational model of development, not only to explain the process but also to realize it using robots in order to establish the design theory of CDR [1]. Also, the physical implementation by robots is helpful to understand the key issues to model the development process.

III. Various aspects of development

A. Normal development of fetus and infant

Recent imaging technology such as 3-D ultrasound movies enabled observation of the various kinds of fetal movements in the womb after several weeks of gestation, and reveals the possibility of fetus learning in the womb [28]. Vries et al. [26] reported that fetal motility started from the early state of “just discern movements (7.5 weeks)” to the later state of “sucking and swallow (12.5 - 14.5 weeks)” through “startle, general movements, hiccup, isolated arm movements, isolated leg movements, head retroflexion, head rotation, hand/face contact, breathing movements, jaw opening, stretch, head anteflexion, and yawn.” Campbell [29] also reported that the eyes of the fetus open around 26 weeks of gestation and that the fetus often touches its face with its hands during embryonic weeks 24 and 27.

Regarding the fetal development of sense, touch is the first sense to develop and then other senses such as taste, auditory, and vision start to develop. Chamberlain stated as follows: just before 8 weeks gestational age, the first sensitivity to touch manifests in a set of protective movements to avoid a mere hair stroke on the cheek. From this early date, experiments with a hair stroke on various parts of the embryonic body show that skin sensitivity quickly extends to the genital area (10 weeks), palms (11 weeks), and soles (12 weeks). These areas of first sensitivity are the ones which will have the greatest number and variety of sensory receptors in adults. By 17 weeks, all parts of the abdomen and buttocks are sensitive. Skin is marvellously complex, containing a hundred varieties of cells which seem especially sensitive to heat, cold, pressure and pain. By 32 weeks, nearly every part of the body is sensitive to the same light stroke of a single hair. Both hearing and vision start about 18 weeks after gestation and develop to complete their perception around 25 weeks [27]. Moreover, it is reported that visual stimulation from the outside of the maternal body can activate the fetal brain [30]. Fig. 1 shows the emergence of fetal movements with the development of fetal senses reflecting the above knowledge.

After birth, infants are supposed to gradually develop body representation, categories for graspable objects, capability of mental simulation of actions, and so on through their learning processes. For example, hand regard at the fifth month means learning of the forward and inverse models of the hand. Table I shows typical behaviors and their corresponding targets to learn.

Thus, human fetuses and infants expose cognitive developmental process with remarkable vigor. However, the early cognitive development of the first year after the birth is difficult to visualize since the imaging technology applicable to this age is still very limited, and the followings are suggested.

TABLE I
INFANT DEVELOPMENT AND LEARNING TARGETS

months	behaviors	learning targets
5	hand regard	forward and inverse models of the hand
6	finger the other’s face	integration of visuo-tactile sensation of the face
	observe objects from different viewpoints	3-D object recognition
7	drop objects and observe the result	causality and permanency of objects
8	hit objects	dynamics model of objects
9	drum or bring a cup to mouth	tool use
10	imitate movements	imitation of unseen movements
11	fine grasp and carry objects to others	action recognition and generation, cooperation
12	pretend	mental simulation

1) We cannot derive the infants’ brain structure and functions from the adults’ ones, nor should do it [31], [32], [33].
2) Brain regions for function development and function maintenance are not the same. During early language development, damage of the legion in the right hemisphere is much more serious than that of the left one [34].
3) The attention mechanism develops from the bottom-up ones such as visual saliency map to the top-down one needed to accomplish the specified task, and the related brain regions shift from posterior to anterior ones [35].
4) Even though the appearances of the performances look similar, their neural structures might be different. Generally, the shift from subcortical to cortical areas is observed from a macroscopic viewpoint. The brain region active for RJA (responding to joint attention) is the same as the region of general attention (the left parietal lobe), but that for IJA (the ability to initiate joint attention) includes the prefrontal area and close to the area for language [35], [36].

B. Facets of development

Here, we briefly review the facets of development in the survey by Lungarella et al. [37] from viewpoints of external observation, internal structure, its infrastructure, and social structure, especially focusing on the underlying mechanisms in different forms. Fig. 2 summarizes the various aspects of the development according to this review.

From the observation of the behaviors, the developmental process of infants can be regarded as one not centrally controlled but instead a distributed and self-organized process. The later structure during the developmental stage is constructed on the former structure that is neither complete nor efficient behavior representation. This is one of the biggest differences from artificial systems [37]. Ecological constraints of infants

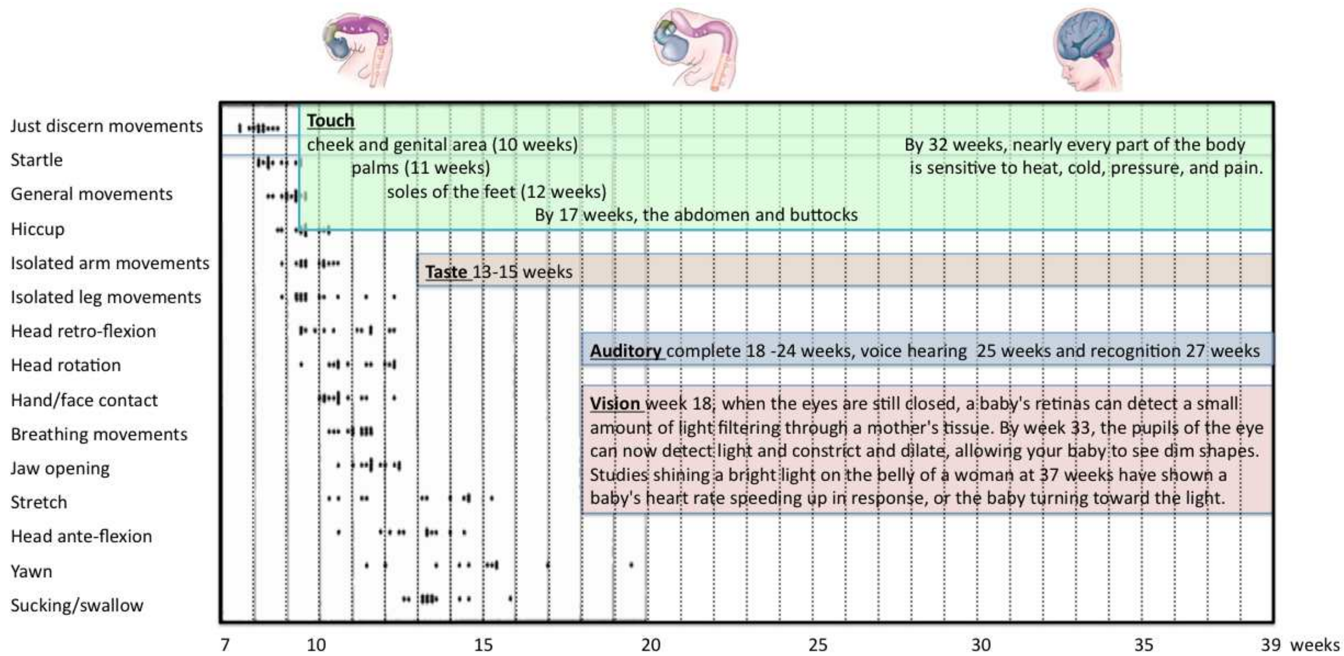

Fig. 1. Emergence of fetal movements and sense (Brain figures on the top are adapted from Figure 22.5 in [25], emergence of movements is adapted from Figure 1 in [26], and fetal senses are adapted from [27])

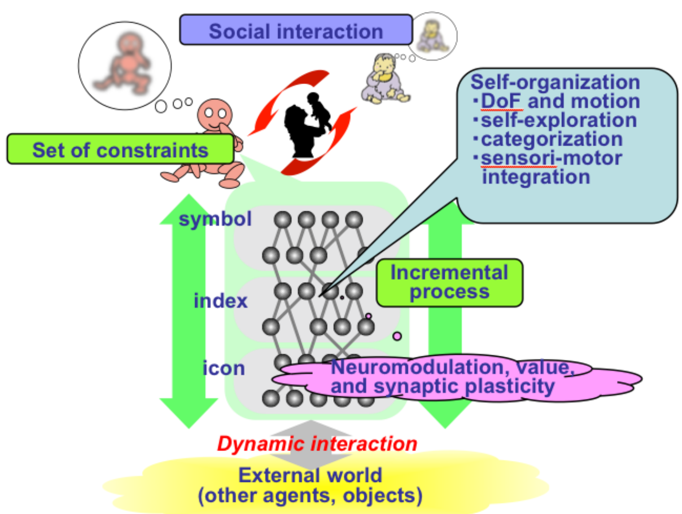

Fig. 2. Various aspects of the development from viewpoints of external observation, internal structure, its infrastructure, and social structure. Here, we briefly review the issue considering the underlying mechanisms in different forms

are not always handicaps but can also serve to promote the development. The intrinsic tendency of co-ordination or pattern formation between brain, body and environment is often referred to as entrainment, or intrinsic dynamics [38]. Self-exploration plays an important role in infancy, in that infants' "sense of the bodily self" to some extent emerges from a systematic exploration of the perceptual consequences of their self-produced actions [39], [40].

The consequence of active exploration and interaction with the environment is regarded as perceptual categorization and concept formation in developmental psychology. Sense and some sort of perception are processed independent of motion, but perceptual categorization depends on the interaction between sensory and motor systems. In the self-organization, some processes are regulated by neuromodulators that relates to value or synaptic plasticity, and there is a study to predict this kind of interaction from the computational model of meta-learning [41].

Macroscopically, the quality of involvement with caregiver or others promotes the infants' autonomy, adaptability, and sociality. Scaffolding by caregiver has an important role in cognitive, social, and skill development. Infants have "sensitive periods" to caregivers' responses, and the caregivers regulate their responses to the infants.

IV. Approach of Cognitive Developmental Robotics

A. Model of cognitive development

Let us consider the model of cognitive development based on the various aspects of development in the previous section. Roughly speaking, it consists of two phases: the individual development at an early stage and the social development through interaction between individuals later on. The former relates mainly to neuroscience (internal mechanism), and the latter to cognitive science and developmental psychology (behavior observation). Intrinsically, both should be seamless, but there is a big difference between them at the representation level for the research target to be understood. CDR aims not at simply filling the gap between them but more challengingly at building a new paradigm that provides new understanding of ourselves and at at the same time new design theory of humanoids symbiotic with us. Hereafter, we briefly show the

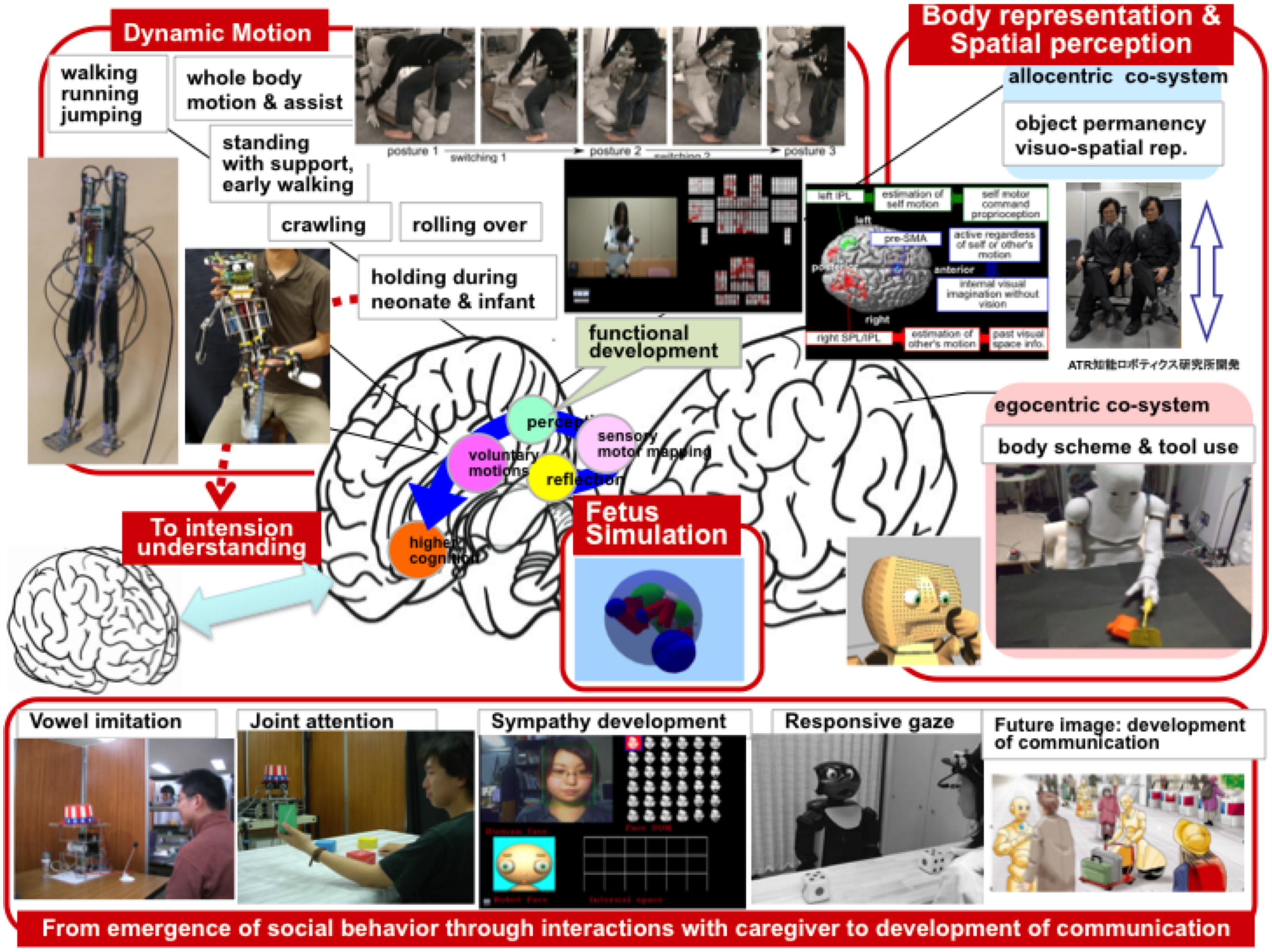

Fig. 3. The model of cognitive development that starts from the fetal sensorimotor mapping in the womb, to the social behavior learning through body representation, motor skill development, and spatial perception.

flow of the development model, and then introduce studies related to CDR and discuss the validity of the model for cognitive development.

The major functional structure of the human brain-spine system is a hierarchical one reflecting the evolutionary process, and consists of spine, brain stem, diencephalon, cerebellum, limbic system, basal ganglia, and neocortex. Here, we regard this hierarchy as the first analogy toward the cognitive developmental model, and the flow of functional development is indicated at the center of Fig. 3, that is, reflex, sensorimotor mapping, perception, voluntary motion, and higher order cognition.

Along this pathway, the first one is the most fundamental structure for motions, that is, the spinal cord - brain stem - cortex network that includes the simulation of fetal sensorimotor development [42]. The next is the mechanism of dynamic motions of whole body from rolling over and crawling, to walking and also jumping (voluntary movements). These kinds of physical implementation of dynamic motions are focused on since the research platform is very important for CDR and related research disciplines. Pneumatic actuators are tested as artificial muscle to generate dynamic motions and to understand the mechanism of humans' dynamic motions (ex., [14], [15], and [16]). The third one is body representation and spatial perception to link the individual development and social one between individuals. There are many works from both natural science (ex., Ogawa and Inui [43] and Iriki et al. [44]) and CDR (ex., Nabeshima et al. [45], Yoshikawa et al. [46], and Fuke et al. [47], [48]). Finally, the developmental of social behaviors ([49]) such as early communication ex., (Rochat et al. [50] and Ogino et al. [51]), vocal imitation (ex., [52], Yoshikawa et al. [53] and Ishihara et al. [54]), joint attention (ex., [55], [56], [57]), and empathy development (ex., [58] and [59]) are introduced, showing what are the keys to trigger each social behavior from a viewpoint of scaffolding by caregiver.

B. CDR approach

CDR consists of two design issues as explained in the proposed model of development: individual cognitive development focusing on computational learning and development mechanisms inside the individual, and social development through interaction between individuals focusing on the environmental design issue including other agents [1]. So far, CDR has put its emphasis on the computational model of cognitive development, but in order to more deeply understand how humans develop, robotics as a new means of reliable reproduction tools should be given. The following is a summary:

A: construction of computational model of cognitive development
1) hypothesis generation: proposal of a computational model or hypothesis based on knowledge from existing disciplines
2) computer simulation: simulation of the processes difficult to implement with real robots such as physical body growth
3) hypothesis verification with real agents (humans, animals, and robots), then go to 1)

B: offer new means or data to know human developmental process → mutual feedback with A
1) measurement of brain activity by imaging methods
2) verification using human subjects or animal ones
3) providing the robot as a reliable reproduction tool in (psychological) experiments

V. Discussion

We have given an overview of the various aspects of cognitive development, and proposed the idea of the developmental model shown in Fig. 3. A part of the references of real robot implementations, computer simulations, psychological experiments with robots or computer simulation, and brain imaging studies are shown as support for the model.

Although we attempted to cover the full range of research topics of cognitive development from fetal simulation to the beginning of communication, we might have missed a number of important issues to be dealt with. Including those issues, we review the whole process.

In the fetal simulation [42] introduced as a model of individual development, the processes and/or consequences of the interaction between neural-musculo-skeletal model (brain and body) and the external environment are reflected on the brain development. This indicates that body and brain are not separable but instead tightly coupled and developed through the interaction with the external environment (in this case, the womb). In this sense, we say "body shapes brain" [10], [11]. The current model is still very simple and missing many other brain regions, sensory organs, and the details of body parts. By adding these regions, organs, and parts, more realistic simulations can be done through mutual feedback with neuroscience, developmental psychology and other related disciplines.

Another extension is to connect with real robot experiments and real infant studies. Actually, the research group of JST ERATO Asada Synergistic Intelligence Project[1] developed prototypes for baby robots based on McKibben pneumatic actuators [60], and tactile sensor suits for a caregiver and a baby in order to measure the mother-infant physical interaction in holding [61]. Some preliminary results are given, but more improvements for the baby robots and a deeper analysis of the data captured in holding are expected.

With regards to the development of motor skills, we focus on the aspect of hardware such as actuators, tactile sensors, and whole body research platform CB^2 for CDR because we put emphasis on the physical embodiment, the central idea of the developmental pathway from motor skills to cognitive functions, and therefore we cannot skip the issue of such equipment for CDR to attack the main issue of cognitive development of humans and robots. McKibben pneumatic actuators and another air cylinder type actuator are found to be useful in generating dynamic and flexible motions compared to conventional electromagnetic motors, and to experimentally verify how a human-like musculoskeletal system works. However, the pathway from motor skills to cognitive functions has not been clear. Observation studies (ex., [62]) imply the connection between motor experiences and cognitive development, but its underlying mechanism is still unclear. How does motor skill development relate to cognitive development, do they "trigger each other" or "interfere"? In addition to the hardware improvements, a new experimental scheme to model the pathway seems necessary.

Body/motor representation and spatial perception is one of the most fundamental issues of CDR, and imaging studies suggest the brain regions related to these representations and cognitive functions, but it is difficult to see from these studies how these functions develop in the brain. Although a number of synthetic approaches were shown to attack this issue, each of them has its own assumptions and limitations that do not always match with the findings in brainscience. More systematic efforts from both sides seem necessary to make the model hypothesized by synthetic approach more realistic and to set up imaging experiments so that the hypothesized model can be easily verified. "Object permanence" can be a good target to make such efforts since it has not been systematically attacked by synthetic approaches although it is an important step to develop higher order cognitive functions.

Reaching and grasping are very important steps toward object manipulation and recognition, and therefore motor skill development and visual attention system should be well-coordinated to realize such actions. In this article, we have touched imaging studies for these actions, but not so much for synthetic approaches since we have been lacking good platforms suitable for developmental study, such as a finger-hand-arm system covered by soft skin with tactile sensors. In such a situation, Giulio Sandini's group has been doing developmental study for object recognition through grasping (ex., [63], [64], [65]) with their hand-arm system. They started from motor and vision primitives and the system learned the sensorimotor mapping and consequently objects for so-called "affordance." The improvement of the platform is necessary, that may lead more analysis on the structural and functional correspondences between the modules in the system and the brain regions.

In the development of social behavior through the interaction between individuals, a caregiver as an active environmental factor explicitly and implicitly affects the cognitive

[1] http://www.jeap.org/

development. Imitation is one of the most essential issues in cognitive development, and there have been many studies in different disciplines such as ethology, developmental psychology, neuroscience, and robotics (ex., [66], [67], [68] and many more). Instead of a thorough survey of imitation in general, here we touched on neonatal imitation and other ones such as vocal imitation from a viewpoint of development. The issue for infants is how to acquire the exact representation of "others," and this is expected to be obtained by elucidating the learning process of the mirror system.

The studies on developmental disorders such as ASD (Autism Spectrum Disorders) and WS (Williams Syndrome) seem useful to construct the computational model of cognitive development that is conversely expected to be able to explain the structure of such disorders. In this process, synthetic approaches such as CDR are very effective, and the meaning of such approaches become deeper, which will eventually lead to the creation of new scientific values of CDR. In conclusion, even though we still have many issues to be attacked, CDR seems the most promising approach to the design principle of cognitive development toward verbal communication.

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