

Emergent Spontaneous Movements Based on Embodiment: Toward a General Principle for Early Development

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Abstract

We investigate whether spontaneous movements, which initiate and guide early development in animals, can be accounted for by the properties underlying embodiment. We constructed computer and robotic models of several biological species with biologically plausible musculoskeletal bodies and nervous systems, and extracted the embodied and motor networks based on inter-muscle connectivities. In computer simulations and robot experiments, we found that the embodied and motor networks had similar global and local topologies, suggesting the key role of embodiment in generating spontaneous movements in animals.

Index Terms: embodiment, developmental model, network analysis

1. Introduction

Through evolutionary processes, the animal body and nervous system have mutually adapted in order to achieve efficient sensorimotor integration within the environment. As a result, various adaptive behaviors can emerge from dynamical interactions between the body, nervous system and the environment. This is possible because the neural system exploits the physics of the body on the one hand, while on the other hand, the body dynamics structures the neural dynamics via sensory information. This constitutes a fundamental property of embodied intelligence [1].

Converging developmental studies have emphasized the significance of learning from as early as the fetal period for motor and cognitive development [2]. In particular, these studies have emphasized the importance of spontaneous movements for early development. Recent detailed ultrasound studies on the emergence of fetal motility revealed that spontaneous behaviors start prior to the completion of the spinal reflex arc [3]. Further, these spontaneous movements play an important role in shaping reflex movements and organizing the nervous system in the spinal cord and brain during development [4][5].

Several researchers have suggested Central Pattern Generators (CPGs) as the neural basis for spontaneous movement [3], but how these spontaneous movements emerge in animals with complex and redundant musculoskeletal systems is still not completely understood. Understanding the neural and biomechanical basis of this underlying mechanism can be useful for understanding how spontaneous movements guide early development.

Further, accumulating evidence from developmental research has revealed species generality in the early developmental stage, for example, the dorso-ventral patterning program that characterizes motor neuron and interneuron generation in the

spinal cord, progressive phases of limb motor development and motor primitives for locomotion [6][7]. These studies raise the question of whether and how a general mechanism guides early development beyond the difference of body, nervous system and their environment. Yet, few studies have answered this question and constructed a theoretical model for early development.

Our aim was to deepen our understanding of general mechanisms of early development in natural organisms by focusing on spontaneous movements. In this paper, we argue that embodiment generates spontaneous movements and guides early development. Since spontaneous movements precede the development of spinal reflex arc and affects the formation of anatomical and functional neural circuits, it is not necessarily reasonable to assume that innate muscle coordination circuits are required for the generation of the spontaneous movements. We thus predicted that embodiment, which structures sensory-motor interactions, intrinsically contains enough information to generate spontaneous movements. To test our hypothesis, we constructed biological models of several animal species, and investigated their movements in both computer simulations and robot experiments. In a series of experiments, we showed that spontaneous movements can emerge according to their species-specific embodiment from the common neural circuit without any pre-defined muscle coordination circuits in all tested species, and suggesting that this principle can apply to a wide range of species.

2. Materials and methods

2.1. Biological systems

We constructed three musculoskeletal vertebrate models in computer simulation: the Zebrafish embryo, canine and human fetus models (Fig. 1(a) ~ Fig. 1(c)). Each of these models had parameters that changed with developmental stage.

In the Zebrafish embryo model, the key parameters that we manipulated were size, muscle configuration and the number of somites during the embryonic stage [8]. The number of somites, that is the number of muscles, increased with development.

We constructed the human fetus model based on previous work by Mori and Kuniyoshi [9]. In the human and canine fetus models, the size, mass, moment of inertia of each body part, joint angle limits, muscle configuration and force were manipulated to match those of the fetuses at a gestational age [10][11]. The canine and human fetus models had 170 and 198 muscles, respectively, in the whole body excluding the finger and face muscles.

For the embryonic and fetal environment, we used the amniotic fluid and uterine wall models produced by Mori and Kuniyoshi [9].

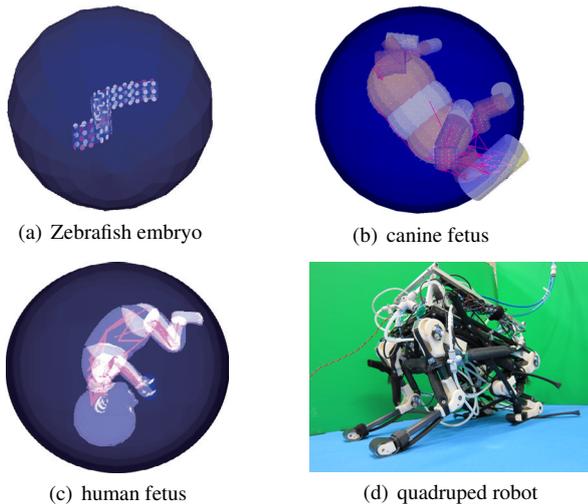


Figure 1: Biological systems. (a)-(c) Blue circle is egg or uterine wall, white and red circle is contact point, and red string is muscle.

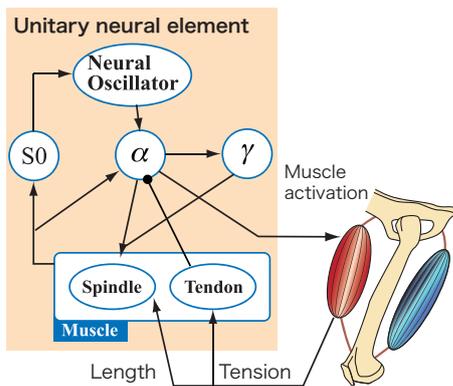


Figure 2: Spinobulbar model. Neural oscillator : neural oscillator neuron model, S_0 : afferent sensory interneuron model, α : alpha motor neuron model, γ : gamma motor neuron model, Spindle : muscular sensory organ model, Tendon : Golgi tendon organ model. Arrow and filled circle represent excitatory and inhibitory connections, respectively.

Further, to examine the hypothesis in a real-world environment, we designed a simple quadruped robot that captured important features of the animal musculoskeletal system (Fig. 1(d)). For actuators, we employed McKibben-type pneumatic artificial muscles that reproduced some of the non-linear properties of biological muscles in terms of damping and elasticity. The muscle configuration and sensory feedback of our robot were compatible with the mono- and bi-articular muscles of a quadruped animal, its muscle spindles and Golgi tendon organs.

For the nervous system, we employed the spinobulbar model developed by Kuniyoshi and Sangawa [12]. This model receives muscle length and tension as sensory input, and then outputs the degree of muscle activation as motor command. Each muscle is independently controlled by a single unit within the spinobulbar model (Fig. 2). These muscles are coupled to each other so that if one muscle moves (i.e. contracts), the other

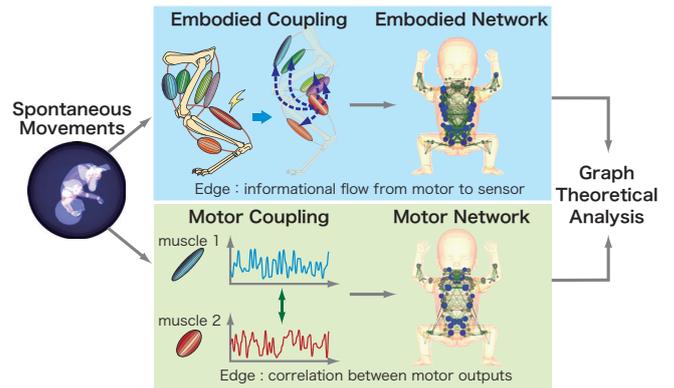


Figure 3: Diagram of measuring and analyzing embodied and motor networks based on inter-muscle connectivities.

muscles change configurations due to the physical constraint of the body (i.e. elongates). Therefore, although individual units of the spinobulbar model are not linked by pre-defined motor coordination circuits, this model can serve to dynamically couple different muscles, and then generate various whole-body movements. In this paper, we refer to *embodied coupling* as such dynamic coupling through the body. This model allows us to investigate whether and how embodiment shapes spontaneous movements through embodied coupling.

2.2. Embodied and motor network analysis

To quantitatively characterize embodiment and spontaneous movements in our biological models, we built networks of muscles with inter-muscle connections defined by sensory and motor activations (Fig. 3).

To characterize embodiment, we extracted the *embodied network* which represents patterns of embodied coupling, that is, how much the motor output of one muscle influences the sensory information of other muscles. We computed this embodied coupling with transfer entropy, which captures patterns of directed interaction and information flow [13].

To characterize spontaneous movements, we extracted the *motor network* by measuring the dynamic motor coupling between muscles. The dynamic coordination of motor commands between muscles was quantified by measuring the Pearson correlation coefficient between motor outputs.

We used standard graph measures to analyze and compare the local and global network properties of both the embodied and motor networks, as well as muscle-specific properties within each network.

3. Experiments

We conducted simulations with the Zebrafish embryo, canine and human fetus models, using the open dynamics engine for simulating rigid body dynamics [14]. We set the time step of the simulation to 1 ms, and ran each simulation for 1,000 s.

We also did several experiments with the quadruped musculoskeletal robot. The robot was mounted with a CPU board running a real-time OS that sent pressure values as motor command and received the length and tension of each pneumatic muscle as sensory feedback every 7.5 ms. One external PC communicated with the CPU board every 100 ms and computed the

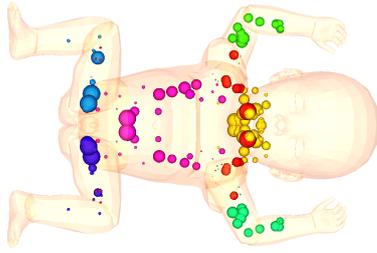


Figure 4: Module decomposition of the motor network in the human fetus model. Circle is muscle, size of circle is within-module degree and colors depict community assignments. The number of modules is 7.

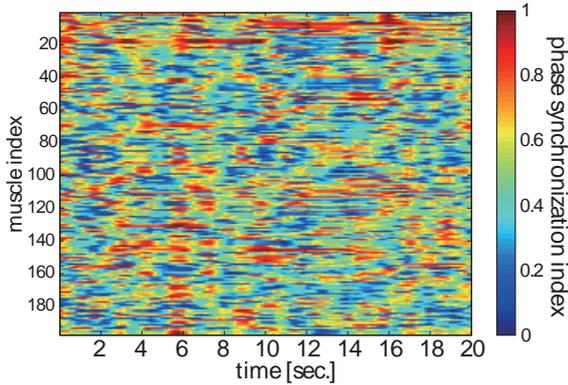


Figure 5: Time series of the instantaneous phase synchronization index (for 200 ms) between one muscle and the others.

neural dynamics every 1 ms.

When we constructed the embodied and motor networks, we used muscle length from the muscle spindle model as sensory information and motor commands from the alpha motor neuron model as motor information.

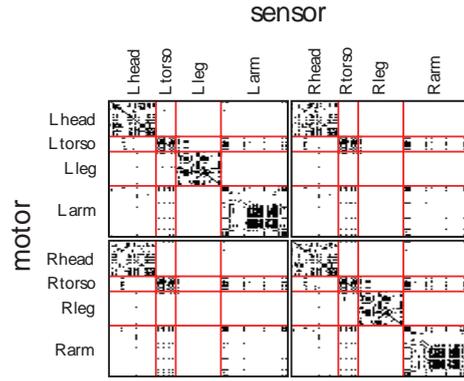
3.1. Emergent movements

Throughout the simulation experiments, the Zebrafish embryo, canine and human fetus models exhibited mixtures of periodic and aperiodic complex movements. In robot experiments, we also observed the robot transitioned from forward to backward movements, and after several steps it regenerated forward movements. Among other behaviors, there were forward-only and backward-only movements as well as jumping-like motion. Movie of the experiments is available on the first author website¹.

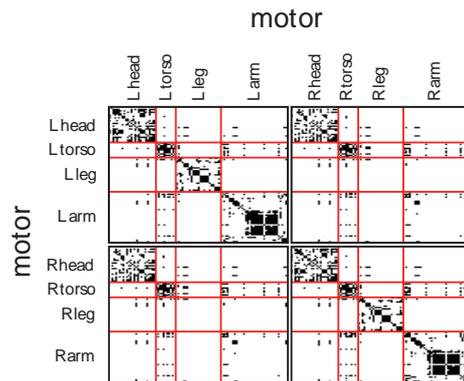
We also investigated the modular architecture in the motor networks to reveal movement modules. We found that modular partition of the canine and human fetus models corresponded to groups of the body parts, such as each leg and arm (Fig. 4).

To reveal dynamic coordination relationship at a time scale of movement unit, we calculated the phase locking value [15], which can identify transient synchrony between muscle pairs on a millisecond scale. Figure 5 shows temporal evolution of the instantaneous synchrony between one muscle and the others.

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(a) Embodied network.



(b) Motor network.

Figure 6: Binary networks of the human fetus model. Black squares represent existing connections.

Table 1: Network properties in the human fetus model.

	Embodied	Motor
clustering coefficient	5.63	7.13
characteristic path length	1.74	1.69
modularity	0.69	0.70
small worldness	3.24	4.22
assortativity	0.44	0.33

3.2. Relationship between embodied and motor networks

We carried out a detailed analysis of the embodied-motor networks in all four biological systems (Fig. 6, Table 1). We computed characteristic measures of network organization, including the (normalized) clustering coefficient, (normalized) characteristic path length, modularity, small worldness and assortativity. Normalized measures were computed relative to a set of 100 comparable random graphs.

Both networks showed a high level of clustering coefficient (>1) and a high level of characteristic path length (~ 1), confirming a small-world organization of networks. Modularity of both networks was more than 0.3, suggesting the presence of a significant modular architecture in the networks. Assortativity characterizes network resilience properties against node removal. Both networks showed positive assortativity coefficients, indicating that properties of these networks are relatively robust against the removal of nodes.

Further, we compared the node-specific degree, strength and betweenness centrality of the embodied and motor networks. These measures identify node centrality, which is useful diagnostic for comparing topologies. As the results, these measures within embodied networks were significantly correlated with those within the motor network (e.g. degree $r = 0.76$, strength $r = 0.77$ and betweenness centrality $r = 0.60$ for the human fetus model; Student's t-test $p < 0.001$, $n = 198$).

We note a high level of consistency of these graph measures, suggesting substantial agreement in the topological organization between the embodied and motor networks.

3.3. Relationship between canine and human fetus models

Dominici et al. showed the similarity of motor primitives in locomotor system between humans, other mammals and birds [7].

So, we compared embodied and motor networks with canine and fetus models in the muscles shared by two species according to anatomical knowledge. As the above global graph measures, two models have similar topology both in embodied and motor networks. Node-specific measures also were significantly correlated between emergent motor networks in the canine and human fetus models (degree $r = 0.45$, strength $r = 0.46$ and betweenness centrality $r = 0.38$; Student's t-test $p < 0.001$, $n = 170$).

4. Discussion

Animals are dynamically coupled to their environments, with embodiment shaping the structure of sensory input, and sensory information determining neural dynamics. In this paper, we explained how such mechanisms occur in neural-body coupling using the biological systems. We also explained how embodiment produces spontaneous movements and attempted to characterize this as a general phenomenon transgressing differences in embodiment. To examine our hypothesis, we introduced a set of quantitative network analysis aimed at capturing the relationship between embodiment and spontaneous movements. We exemplified their use by running computer simulations and robot experiments which produced spontaneous movements.

In the computer simulation and robot experiments, we found the embodied and motor networks share similar topologies of global and node-specific graph metrics. These results suggest spontaneous movements can emerge according to their species-specific embodiment without any pre-defined innate muscle coordination circuit.

Further, we observed the neural-body coupling based on the biological body and nervous system was capable of producing transient synchronization between localized body parts, and resulted in complex and interrelated spatiotemporal behaviors. Fast motor dynamics exhibit intermittent synchronization and desynchronization on a time scale of hundreds of milliseconds, enabling the system to continually explore a repertoire of functional motor coupling.

Experimental studies on animal movements have suggested the existence of motor primitives, or motor synergies, and have studied their organization as a result of learning [4]. However, their neural basis and mechanisms of organization during development remain poorly understood. Our results suggest the embodiment possesses lots of regularities that restrict the number of coordination and allows the animal to explore a variety of embodied dynamics via neural-body coupling. We believe that these explorations via spontaneous movements guided by embodiment could bring about organization of motor synergies

as a result of modulation and selection of the motor repertoires based on sensory information and motives.

In comparing the canine and human fetus models, we discovered similarities in embodiment and spontaneous movements. Although further research is needed to understand the precise cause and potential implication of the above findings, it is reasonable to assume that similarities in the embodiment and spontaneous movements create, through developmental processes, similarities in motor development and motor synergy for locomotion [6] [7].

In this paper, we quantified the contribution of embodiment in shaping spontaneous movements with biologically realistic systems. We discussed the possibility that the spontaneous movement based on embodiment is a key principle for the early development of natural organisms. In future works, we will investigate and compare how the spontaneous movement shapes coordination neural circuits and guides motor and cognitive development using biological systems of various species at various developmental stages.

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