

# ADAPTIVITY VIA ALTERNATE FREEING AND FREEZING OF DEGREES OF FREEDOM

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## ABSTRACT

Starting with fewer degrees of freedom has been shown to enable a more efficient exploration of the sensorimotor space. While not necessarily leading to optimal task performance, it results in a smaller number of directions of stability, which guide the coordination of additional degrees of freedom. The developmental release of additional degrees of freedom is then expected to allow for optimal task performance and more tolerance and adaptation to environmental interaction. In this paper, we test this assumption with a small-sized humanoid robot, that learns to swing under environmental perturbations. Our experiments show that a progressive release of degrees of freedom alone is not sufficient to cope with environmental perturbations. Instead, alternate freezing and freeing of the degrees of freedom is required. Such finding is consistent with observations made during transitional periods in acquisition of skills in infants.

Keywords: Developmental robotics, embodiment, neural oscillator, freezing and freeing of degrees of freedom.

## 1. INTRODUCTION

The field of developmental psychobiology puts forward the hypothesis that constraints in the sensory system and biases in the motor system may have an important adaptive role in ontogeny. In this paper we will consider morphological limitations in the motor apparatus of a developing system as instances of ontogenetic adaptations, i.e. with an immediate adaptive role at a particular stage of development and not only beneficial for the emergence of stable sensorimotor coordinations with an increased tolerance to environmental perturbations, but also facilitating or even providing for early stages of learning. Later stages of learning in turn are bootstrapped by higher-valued settings of the morphological resources under consideration. A few telling examples of morphological limitations present at birth in the sensory, motor, and neural systems, are the accommodative system [12], working memory and attention span [3], the inefficiency of movements, and the poor postural control of head, trunk, arms, and legs [11].

In our context, this means that an initial reduction of the number of biomechanical degrees of freedom may be necessary (but not sufficient) for learning a new skill. Preliminary but descriptive evidence that in some tasks the activity of the number of degrees of freedom is initially reduced and subsequently increased has been collected by Bernstein [1]. He showed that a freezing of the number of degrees of freedom is followed, as a consequence of *experiment and exercise*, by the lifting of *all* restrictions, and the incorporation of *all* possible degrees of freedom. There are several other studies that have reported a freezing of joint segments in the initial stage of learning a motor task. These include the learning of handwriting signature by adults with the non-dominant limb [8], a ski simulator task [13], and studies performed by Jensen et al. [5] on the development of infant leg kicking between 2 weeks and 7 months of age.

## 2. SIMULATIONS OF LIMITATIONS

A few attempts to address developmental issues with simulated environments and real-world devices have been made. Typically these systems start with a set of initially constrained (morphological) resources, which are subsequently released.

Elman [3] described artificial neural networks which are only able to learn the processing of complex sentences when handicapped by severe capacity limitations. These limitations are later released while the networks gradually mature to an *adult-like* state. Interestingly, in their initial stage, these networks fail to learn fully formed or *adult-like* sentences. Taga [10] reported computer simulations of the development of bipedal locomotion in human infants. By freezing and freeing the degrees of freedom of the neuro-musculo-skeletal system, the *U-shaped changes in performance* typically observed in the development of the stepping movement can be reproduced. Taga's model seems to suggest that these changes can be understood in terms of the release of initially constrained morphological resources. Another implementation of these ideas was proposed by Berthouze and Kuniyoshi [2]. They performed various experiments with a nonlinear redundant four degrees of freedom robotic vision

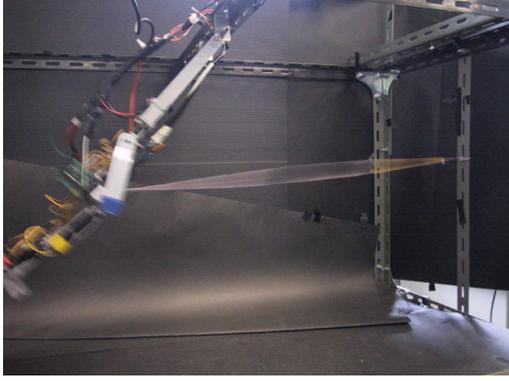


Figure 1: Humanoid robot used in our experiments.

system. In their experiments, two out of four available degrees of freedom are delayed in order to reduce the risk to get trapped in *stable but inconsistent minima*. According to the authors, the advantage of the adoption of this *developmental strategy* is a reduction of the learning complexity in each joint and a faster stabilization of the adaptive parameters of the controllers.

### 3. EXPLORING PHYSICAL MATURATION

In [6], we investigated the impact of morphological changes on the control performance of a **given neural control structure**. Taking as example the exploration of swinging behaviors (pendulation) in a small-sized humanoid robot, we proposed a comparative analysis between outright use of the full body for exploration and progressive exploration using a mechanism of developmental freeing of the degrees of freedom. It was shown that with a developmental release of the second degree of freedom, the system would always converge into the same smooth, and in-phase swinging behavior with maximal amplitude (resonant control).

In this paper, we follow-up on the previous experiments by incorporating proprioceptive information and focussing on the issue of tolerance and adaptivity to perturbations, in particular physical constraints and external interventions.

### 4. EXPERIMENTAL SETUP

The experimental setup consists of a small-sized humanoid robot with 12 degrees of freedom (DOF). With its redundant DOF, it allows for enough control complexity. Through two thin metal bars fixed to its shoulders, the robot is attached to a supportive metallic frame, in which it can freely oscillate in the vertical (sagittal) plane (see figure 1).

Each leg of the robot has five joints, but only two of them - hip and knee - are used in our experiments. Each joint is actuated by a high torque RC-servo module. These

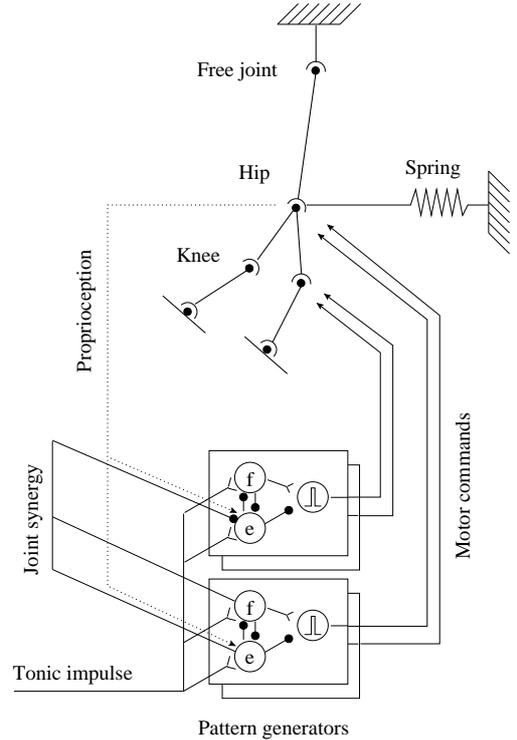


Figure 2: Schematics of the experimental system and neural control architecture. Joint synergy is only activated in experiments involving coordinated 2-DOF control.

modules do not provide any form of sensory feedback about the position of the joint. Appropriate sensory information however is simulated by means of an external camera, which is used to track colored markers placed on the robot limbs. This sensory information gives feedback on the kinematic state variables (anatomical angles) of the robot.

### 5. NEURAL CONTROL ARCHITECTURE

A schematic of the neural control architecture is shown in figure 2. It is based on neural oscillators<sup>1</sup>, which are well-studied control structures and which allow for distributed control.

Each neural oscillator is modelled by the following set of differential equations, derived from [7]:

$$\begin{aligned}\tau_{u_f} \dot{u}_f &= -u_f - \beta[v_f]^+ - \omega_c[u_e]^+ - \omega_p[F_{eed}]^+ + te \\ \tau_{u_e} \dot{u}_e &= -u_e - \beta[v_e]^+ - \omega_c[u_f]^+ - \omega_p[F_{eed}]^- + te \\ \tau_{v_f} \dot{v}_f &= -v_f + [u_f]^+ \\ \tau_{v_e} \dot{v}_e &= -v_e + [u_e]^+\end{aligned}$$

<sup>1</sup>Such control structures are not novel. Our focus is not on control structures per se but rather on how they interact with each other and with the world through the body.

where  $u_{f,e}$  is the inner state of the neuron  $f$  (flexor) or  $e$  (extensor),  $v_{f,e}$  is a variable representing the degree of adaptation or self-inhibition effect of the neuron,  $te$  is a tonic excitation (external input),  $\beta$  is an adaptation constant,  $\omega_c$  is a coupling constant controlling the mutual inhibition of neurons  $e$  and  $f$ , and  $\omega_p$  is a variable weighting the feedback  $F_{eed}$ .  $\tau_u$  and  $\tau_v$  are time constants of the inner state and adaptation effect. The operators  $[x]^+$  and  $[x]^-$  return the positive (respectively negative) portion of  $x$ .

Joint synergy between hip and ankle units is implemented by feeding the flexor unit of the knee oscillator with the output of the flexor and extensor units of the hip controller. A factor  $-\omega_s([u_f^h]^+ + [u_e^h]^+)$  is added to the term  $\tau_{u_f}\dot{u}_f$  in the flexor unit of the knee oscillator.  $u_f^h$  and  $u_e^h$  are the inner states of the flexor and extensor units in the hip oscillator.  $\omega_s$  is the intersegmental coupling constant.

As in [9], each neural oscillator is used as a neural rhythm generator. Its output activity  $y$  is given by  $y = u_f - u_e$ , i.e. by the difference between the activities of the flexor and extensor neurons. This value is then fed to a pulse generator whose activity at time  $t$  is given by:

$$pg^t = te(\text{sgn}(y^t) - \text{sgn}(y^{t-\delta t}))$$

$\text{sgn}(x)$  is the sign function and  $te$  is the tonic excitation defined above. The kicking motion  $pg^t$  serves as control signal for the servo motor of the corresponding joint.

Unless specified otherwise, the following control parameters were kept constant throughout the study:  $\beta = 2.5$ ,  $\omega_c = 2.0$ ,  $te = 20$  for the hip (respectively  $te = 15$  for the knee). Other parameters were set as discussed in the text.

## 6. EXPERIMENTAL DISCUSSION

We organized our experiments so as to provide the basis for a comparative analysis of different learning strategies, from a physical and from a neural point of view. Movements of the robot were analyzed via the recording of its hip, knee and ankle positions. Same initial conditions were used in all experiments, with the humanoid robot starting from its resting position. Our experiments can be divided into three categories:

1. **1-DOF exploratory control.** Left and right hip servo motors are fed with identical motor commands (from a single oscillator unit). Other joints are stiff, starting from their resting position.
2. **2-DOF exploratory control.** Each joint (hip, knee) is controlled by its own oscillator unit. Two cases are considered: (a) independent oscillator units and (b) coordinated units via an intersegmental coupling constant.

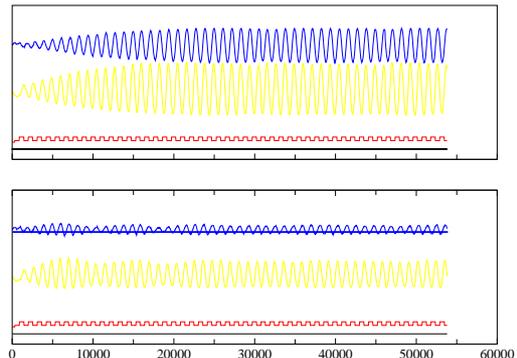


Figure 3: Resonant oscillations for  $(\tau_u = 0.065, \tau_v = 0.6)$  without perturbations (top). Resulting behavior under perturbations (bottom). In each graph, the time-series denote motor impulses (bottom), ankle position (middle) and hip position (top). The horizontal line in the lower graph corresponds to the visual position of the location after which the rubber band is extended. The horizontal axis denotes time in  $ms$ .

3. **Bootstrapped 2-DOF exploratory control.** The second degree of freedom is released and controlled while the system is in the stationary regime obtained in the 1-DOF configuration. Again, independent and coordinated cases are considered.

### 6.1. Introducing nonlinear perturbations

In order to study the effect of environmental interaction during learning, we introduced an asymmetric nonlinear perturbation in the experimental setup. As shown in figure 2, the humanoid is attached at hip-level to a thread which connects to the supportive frame via a rubber band. The rubber band is only extended when the robot is tilted backwards by at least 10 degrees<sup>2</sup>. To illustrate the effects of this perturbation, we configured the hip controller with the parameters found in our previous study to lead to resonant behavior. As shown by figure 3, oscillations of the hip are significantly dampened to less than 10 degrees amplitude.

### 6.2. 1-DOF exploratory control

Goldfield [4] suggested that *the goal of exploration by an actor may be to discover how to harness the energy being generated by the on-going activity, so that the actual muscular contribution to the act can be minimized*. A systematic exploration of the parameter space in the case of an unperturbed system was performed by Lungarella and Berthouze [6]. A full spectrum of oscillatory behaviors was observed,

<sup>2</sup>This setting was kept constant throughout the study. Its role could be explored more systematically in future work.

ranging from exact anti-phase to in-phase oscillations of the legs with respect to the body motion. Without any external intervention, the system would settle into a stationary regime, to which it would return even after strong external perturbations.

In this follow-up study, exploration of the control parameters was realized by a stochastic exploration of the neural oscillator parameter space. We focussed on two parameter settings:  $(\tau_u = 0.035, \tau_v = 0.65)$ , and  $(\tau_u = 0.06, \tau_v = 0.65)$ , with  $\omega_p^h \in [0.0, 7.0]$  for the first setting and  $\omega_p^h \in [0.0, 20.0]$  for the second setting. In the first case, all experiments lead to a stationary regime, robust to external perturbations (e.g., manual push). Two of the resulting time-series are shown in figure 4. In the second case a variety of behaviors was observed. For extreme values of  $\omega_p^h$ , no sustained oscillations could be found.

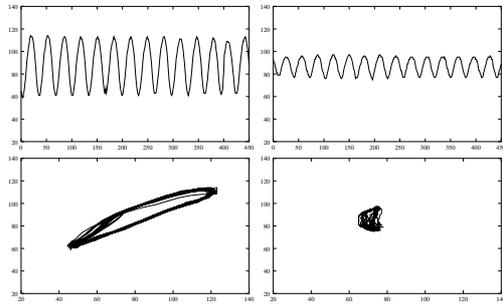


Figure 4: Time-series of hip position (top) and ankle-hip phase plots (bottom) for  $\omega_p^h = 0.25$  (left) and  $\omega_p^h = 4.0$  (right).  $(\tau_u = 0.035, \tau_v = 0.65)$  in both cases. The horizontal axis denotes time in *ms*.

These results confirm our previous findings. The control parameter space is very large and rugged (parameters taken in a small neighborhood do not necessarily yield qualitatively similar results). Adaptivity to external perturbations or optimal task performance require very fine tuning. However, all configurations lead to a stationary regime of hip oscillations, though the hip-ankle phase plot is not necessarily stationary. We hypothesize that this relative robustness will help bootstrap the coordination of multiple degrees of freedom.

### 6.3. 2-DOF exploratory control

#### Independent control

Because an exhaustive exploration of the parameter space for two independent neural controllers is not plausible, we restricted the hip control parameters to the two cases described above. In both cases, a sparse exploration of the knee neural oscillator parameters was realized with  $\tau_u^k \in [0.02, 0.09]$  and  $\tau_v^k \in [0.35, 0.8]$ . Proprioception was fed to

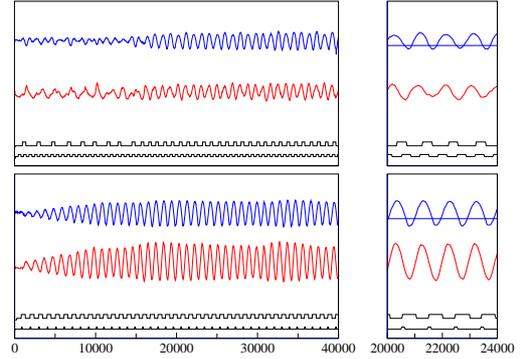


Figure 5: Co-existing regimes for  $\omega_s = 0.0$  and  $\tau_u^h = 0.06, \tau_v^h = 0.65, \tau_u^k = 0.035, \tau_v^k = 0.4$  (top). Unique in-phase oscillatory regime with  $\omega_s = 1.0$  (bottom). In each graph, the time-series denote hip and ankle positions, hip and knee motor commands (from top to bottom). Right-hand windows are close-ups on the time-series. The horizontal axis denotes time in *ms*.

the hip unit only, with a gain  $\omega_p^h = 2.0$ . All experiments yielded the same qualitative behavior: Stationary low-amplitude (30 units) hip oscillations and non-stationary ankle movement.

With a lower gain, the hip motor commands are not entrained as much to overall oscillations and physical entrainment between knee and hip motor commands can occur because the phase shift is slower.

To further confirm the hypothesis, a last batch of experiments was carried out in which the knee control unit was also fed with proprioceptive feedback. After fixing the knee unit parameters to  $\tau_u^k = 0.06, \tau_v^k = 0.65$ , the knee proprioceptive feedback gain  $\omega_p^k$  was varied in the interval  $[0.0, 8.0]$ . Oscillatory behaviors were found to be qualitatively similar to those obtained without proprioception to the knee, namely, low-amplitude hip oscillations, stationary regime robust to external perturbations. With an increase in gain, ankle oscillations became increasingly in phase with the hip oscillations and the overall behavior was smoother.

With different knee parameters however  $\tau_u^k = 0.02$  and  $\tau_v^k = 0.35$ , a wide range of behaviors was observed, from non-stationary and non-smooth ankle behavior to in-phase and stationary oscillations. With an increase in the the knee proprioceptive gain, phase shifts became stronger and stationary regimes were not sustained.

#### Joint synergy

Based on the findings of our previous study, and also on the physics of the human motor system, we hypothesized that an intersegmental coupling between knee and hip control units would enable neural entrainment to take place be-

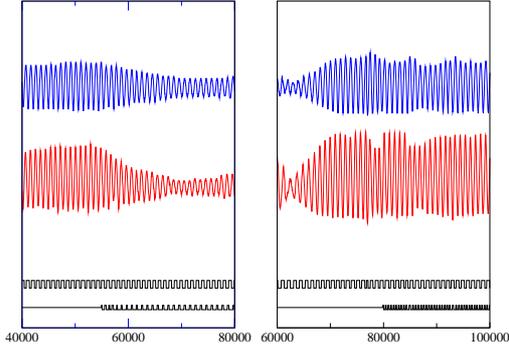


Figure 6: Results of the release of an additional degree of freedom after stabilization in a 1-DOF configuration. Left: ( $\tau_u^h = 0.045, \tau_v^h = 0.65$ ) and ( $\tau_u^k = 0.025, \tau_v^k = 0.45$ ). Right: ( $\tau_u^h = 0.06, \tau_v^h = 0.65$ ) and ( $\tau_u^k = 0.025, \tau_v^k = 0.35$ ). From top to bottom, the time-series denote hip and ankle positions, hip and knee motor commands. The horizontal axis denotes time in *ms*.

tween the two control units. In our experiments, this coupling is controlled by way of the coupling constant  $\omega_s$  (see section 5).

This gain plays a crucial role. With too low a value, the coordination between hip and knee oscillators is very loose and we observe results qualitatively similar to the independent case. With a high value (here, 1.0), a strong coupling occurs and because the lower limb is mainly driven by the hip control unit, the system essentially becomes a flexible 1-DOF system [6]. To illustrate this point, we carried out the following experiments. The hip unit parameters were set to ( $\tau_u^h = 0.06, \tau_v^h = 0.65$ ). The knee control parameters were set so that with an intersegmental coupling  $\omega_s = 0.0$ , multiple regimes would co-exist. The following values were used: ( $\tau_u^k = 0.035, \tau_v^k = 0.4$ ). The proprioceptive feedback gain to the hip was set to 2.0 (its critical value as determined experimentally). With  $\omega_s = 1.0$ , the system was observed to stabilize into a stable regime in which hip and knee oscillated in phase (see motor commands in the close-ups of figure 5). Interestingly, it can be noted that the knee kicking motion occurs only shortly before the robot is reaching the point after which the rubber band is extended. From an intuitive point of view, such behavior could be optimal task performance.

### Bootstrapped 2-DOF exploratory control

Taking inspiration from observations made in developmental psychology regarding the role of freezing and freeing of degrees of freedom in the development of infants' locomotion skills, we experimented with a controlled release of the second degree of freedom after the system has reached sta-

tionary regime in a 1-DOF configuration. 1-DOF configurations such as discussed earlier were selected, not necessarily close to the resonant solution. The reaching of the stationary regime was visually evaluated by the experimenter and the second degree of freedom was then released.

Unlike in our previous studies, where all configurations led to a stable, in-phase stationary regime with large amplitude, the introduction of the second degree of freedom induced different behaviors, showing quite a high sensitivity to the values of the knee control parameters. On the one hand, the introduction of the second degree of freedom can induce a phase shift which results in dampened oscillations. Such phenomenon was found to be repeatable and robust to external perturbations. On the other hand, when the 1-DOF regime is close to resonant control, the oscillatory behavior is left unchanged by the addition of a second degree of freedom - see figure 6.

In our experiments, we did not observe any instance where the introduction of the second degree of freedom lead to better task performance. However, various cases were observed in which the release led to a collapse of the hip oscillations. In such cases, we froze again the second degree of freedom. After re-freezing, the system returned to an oscillatory behavior, typical of its 1-DOF configuration. With a subsequent release of the degree of freedom, that behavior was sustained. Under external perturbations however, it collapsed. With another cycle of freezing and freeing, it recovered. Though further experiments are necessary, this result is interesting in that it confirms observations made by some developmental psychologists. Three phases in the acquisition of some locomotion skills were reported by Goldfield [4]: (1) inability to control excessive degrees of freedom which pushes infants outside the limits of postural stability, (2) reduction of degree of freedom to simplify control and (3) controlled release of degree of freedom. Empirical evidence for the effect of alternate freezing and freeing phases is shown in figure 7. The close-ups on the right-hand side show that although the control parameters have not been changed, the kicking pattern of the knee has changed between subsequent releases.

## 7. FUTURE WORK

In this paper, we set ourselves to empirically validate our hypothesis that physical limitations inherent to body development could be beneficial to the emergence of stable sensorimotor configurations and allow for more tolerance and adaptivity to environmental interaction. Using experiments with a small-sized humanoid robot under nonlinear environmental constraints, we proposed a comparative analysis between outright use of the full body for exploration and progressive exploration using a developmental cycle of freezing and freeing of the degrees of freedom. Experiments on

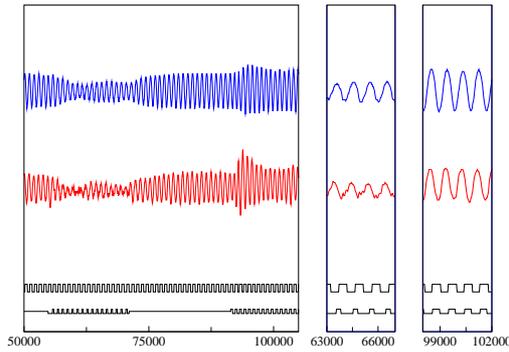


Figure 7: Effect of alternate freeing and freezing of the knee. Neural parameters are unchanged and set to  $\tau_u^h = 0.035$ ,  $\tau_v^h = 0.65$ ,  $\tau_u^k = 0.055$ ,  $\tau_v^k = 0.45$ ,  $\omega_p^h = 0.5$  and  $\omega_s = 0.5$ . From top to bottom, time-series denote hip and ankle positions, hip and knee motor commands. Right-hand graphs are close-ups on the two different regimes. The horizontal axis denotes time in *ms*.

1-DOF exploratory control showed that some stationary oscillatory behavior is obtained for a wide range of parameters. Optimal performance is unlikely to occur and would require very fine tuning. It is even more so with an outright use of two degrees of freedom. The control parameters space is very rugged and there is no continuity in a neighborhood of control parameters. Coupling control units results in more stable behaviors, which can be attributed to neural entrainment between control units. Our last set of experiments on the developmental release of degrees of freedom is inconclusive as to the interest of a freeing phase after stabilization in 1-DOF configuration. However, it showed that, as observed in developmental psychology, alternate phases of freezing and freeing are necessary when exploration leads the system outside its area of postural stability.

## 8. REFERENCES

- [1] N. Bernstein, *The Coordination and Regulation of Movements*, Oxford: Pergamon, 1967.
- [2] L. Berthouze and Y.Kuniyoshi,Y., “Emergence of categorization of coordinated visual behavior through embodied interaction”, *Machine Learning*, 31, pp.187-200, 1998.
- [3] J.L. Elman, “Learning and development in neural networks: The importance of starting small”, *Cognition*, 48, pp.71-99, 1993.
- [4] E.C. Goldfield, *Emergent Forms: Origins and Early Development of Human Action and Perception*, Oxford University Press, New York, 1995.
- [5] J. Jensen, E. Thelen, B.D. Ulrich, K. Schneider and R.F. Zernicke, “Adaptive dynamics of the leg movement patterns in human infants: Age-related differences in limb control”, *Journal of Motor Behavior*, 27, pp.366-374, 1995.
- [6] M. Lungarella and L. Berthouze, “Adaptivity Through Physical Immaturity”, *Proc. of the 2nd Int. Workshop on Epigenetic Robotics*, pp.79-86, 2002.
- [7] K. Matsuoka, “Sustained oscillations generated by mutually inhibiting neurons with adaptation”, *Biological Cybernetics*, 52, pp.367-376, 1985.
- [8] K.M. Newell and R.E.A. van Emmerik, “The acquisition of coordination: Preliminary analysis of learning to write”, *Human Movement Science*, 8, pp.17-32, 1989.
- [9] G. Taga, “Self-organized control of bipedal locomotion by neural oscillators in unpredictable environments”, *Biological Cybernetics*, 65, pp.147-159, 1991.
- [10] G. Taga, “Freezing and freeing degrees of freedom in a model neuro-musculo skeletal systems for the development of locomotion”, *Proc. of the 16th Int. Society of Biomechanics Congress*, pp.47, 1997.
- [11] E. Thelen and L. Smith, *A Dynamic Systems Approach to the Development of Cognition and Action*, MIT Press, Cambridge, MA, USA. A Bradford Book. 1994.
- [12] G. Turkewitz and P.A. Kenny, “Limitations on input as a basis for neural organization and perceptual development: A preliminary theoretical statement”, *Developmental Psychology*, 15, pp.357-368, 1982.
- [13] B. Vereijken, R.E.A. van Emmerik, H.T.A. Whiting and K.M. Newell, “Free(z)ing degrees of freedom in skill acquisition”, *Journal of Motor Behavior*, 24, pp.133-142, 1992.