

# Learning to bounce: First lessons from a bouncing robot

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## Abstract

The study of how infants learn to bounce, while being supported by a harness attached to a spring, sheds light on how infants learn to exploit the dynamics of their exploratory motion. The emerging rhythmical activity – result of an entrainment among neural system, musculo-skeletal system, and surrounding environment – is a salient characteristic of a developing body control during the first year of life. In this paper, we describe and discuss the results of four preliminary experiments realized with a small-sized humanoid robot harnessed in a jolly jumper, and whose leg joints are controlled by neural oscillators. While the two first experiments see the robot oscillate freely in space, the last experiments have the robot touch the ground during oscillations so as to characterize the effects of ground interaction. An appropriate choice of the parameters of the neural oscillators lead to sustained and stable bouncing.

## 1. Introduction

While the importance of active exploration of objects and events in infants has since long been acknowledged by developmental psychologists [1, 2], little attention has been paid to the information available to the infant as a result of his or her own *self-exploratory* acts. One of the goals of self-exploration may be “to ascertain a state of awareness about the self and its environment by means of activities which involve the gathering of information specific to stable regions in the high-dimensional space of possible actions” [3, p. 167] [see also 4, 5]. This process of self-exploration could lead to the creation of new and emergent forms of activity or could help the infant discover more effective ways of harnessing the energy being generated by on-going bodily activities [3, 6, 7]. In other words, the exploration of the individual’s own capacities is one of the primary driving forces of development and change in behavior, and infants have to explore, discover, and select – among the myriad of available solutions – those that are more adaptive, efficient, and

effective [see 8]. Piaget [9] emphasized that when infants perform movements over and over again, they are in fact exploring their own action systems. Similarly, Von Hofsten [10] suggested that exploratory actions, which traditionally have been thought of as actions focused on the external world, may as well be focused on the infant’s own action system.

In the last two decades, a growing body of evidence has shown that the control of movements resulting in particular (exploratory) actions is not determined by innate mechanisms alone, but rather, emerges from the dynamics of a sufficiently complex action system interacting with its surrounding environment [3, 11, 12, 13, 14], i.e., the dynamic landscape of the exploratory activities displayed by infants is modulated by the interaction dynamics of the infant actor and its surroundings. In the wake of Taga [12], we suggest that given a particular task-environment, movements emerge from entrainment among (possibly spontaneous) activity of the musculo-skeletal system, neural system, and the surrounding environment.

The paper is organized as follows: in Section 2, we introduce our task-environment (spring-supported bouncing) and describe its implications in the context of development of motor skills. These implications motivated our robot experiments. We then introduce our experimental setup (Section 3), which is followed by a report of our experiments (Section 4). Finally, we summarize and discuss our main results and conclude by pointing out some future directions.

## 2. Implications of Infant Bouncing

Our interest for *infant bouncing* originates from a longitudinal study performed by Goldfield and colleagues, in which eight 6-months old infants were observed once each week for a period of several weeks, while they learned to bounce. The infants were supported by a harness attached to a spring of known stiffness and

damping. At the onset of each experimental session it was made sure that the infants' soles could "just" touch the floor [15, 3]. Goldfield et al. [15] found that in the course of learning to bounce, the infants' motor activity could be decomposed into an initial *assembly phase* in which kicking was irregular and variable in period, and a subsequent *tuning phase* characterized by bursts of more periodic kicking and long bouts of sustained bouncing, "during which infants seemed to explore the mechanical properties of the mass-spring system (consisting of infant, harness and spring)." A third phase was initiated by a sudden doubling of the bout length, characterized by oscillations of the mass-spring system at its resonant frequency, a sensible rise of amplitude, and a decrease of the variability of the period of the oscillations.

From this study, at least two general implications on the development of *action systems* for human infants, as well as for robotic systems, can be drawn. First, there is no need for a set of preprogrammed instructions or predefined behavioral models of the system. That is, the infants, through a process of *self-discovery*, explored their action space, performing various spontaneous (seemingly random) movements, before discovering that kicking against the floor had interesting consequences. After the *tuning phase*, the infants began to exploit the physical characteristics of the mass-spring system. Goldfield and collaborators hypothesized that, while learning a task, infants may try out different musculo-skeletal organizations by exploring the corresponding parameter space, and by probing the resulting landscapes, driven by the dynamics of the task and by the existing repertoire of skills and reflexes [15, 3].

Secondly, to achieve effective and continuous bouncing – characterized by simultaneous leg extensions – the infants had to learn patterns of intersegmental coordination. This required the exploration of different force and timing combinations for the control of their movements, and the integration of environmental information impinging on various sensory modalities, i.e., visual, vestibular, and cutaneous. Unfortunately, Goldfield et al. [15] did not provide neither a kinematic nor a kinetic analysis of the development of the infants' movement patterns. In line with findings reported in [16, 17, 18], we believe that to reduce the movement complexity, the initial movements were characterized by a tight joint coupling. As learning progressed, the tight intersegmental coupling was loosened, and more complex patterns could be explored.

One of the main motivations for this study resides in our interest for the mechanisms underlying the emergence of coordinated movement patterns via the self-exploration of the sensorimotor space. It

is our contention that self-exploration, while starting off with seemingly random, spontaneous movements, guided by the intrinsic dynamics of the neuro-musculo-skeletal system and its interaction with the environment, may indeed result in spatio-temporally organized motor activity [see also 14, 3, 19].

### 3. Experimental Setup

Our experimental platform consisted of a small-sized humanoid robot with 12 mechanical degrees of freedom (see Figure 1 left and center). The robot was suspended, through a leather harness, to two springs. Each leg of the robot had 3 segments – thigh, shank, and foot – articulated with 5 joints, but only 3 of them – hip, knee, and ankle – were used. The soles of the robot's feet were made of soft and mechanically compliant material. Each joint was actuated by a high torque RC-servo module. These modules are high gain positional control devices and do not provide feedback on the position of the corresponding joint. There was no need to measure the anatomical angles at the hip, knee and ankle, since they were available as the set positions of the RC-servo motors. Exteroceptive and proprioceptive information about body and environment was also taken into account. Ground reaction forces were measured by means of force sensitive resistors (FSR) placed under the feet of the robot. Each foot had two FSR: one positioned at the toe and one at the heel of the foot. Torsional movements around the z-axis were measured with a single-axis solid-state gyroscope, whose output was the angular acceleration  $\omega_z$ . Linear accelerations in the sagittal plane ( $a_x$  and  $a_z$ ) were estimated by a 2-axis accelerometer (see Fig. 1 left).

Figure 1 (right) depicts a schematic representation of the neural control architecture, that was inspired by Taga [12]. The neural rhythm generator or central pattern generator consisted of 6 neural oscillators, each one of which constituted a *resonant circuit* [20] responsible for one joint. In many vertebrate species, central pattern generators seem to generate the rhythm and form of the bursts of motoneurons [21]. We modeled the individual neural oscillators according to the following set of nonlinear differential equations:

$$\begin{aligned}
\tau_u \dot{u}_f &= -u_f - \beta v_f - \omega_c [u_e]^+ - \omega_p [Feed]^+ + te \\
\tau_u \dot{u}_e &= -u_e - \beta v_e - \omega_c [u_f]^+ - \omega_p [Feed]^- + te \\
\tau_v \dot{v}_f &= -v_f + [u_f]^+ \\
\tau_v \dot{v}_e &= -v_e + [u_e]^+ \\
y_{out} &= u_f - u_e
\end{aligned}$$

where  $u_e$  and  $u_f$  are the inner states of neurons  $e$  (extensor) and  $f$  (flexor),  $v_e$  and  $v_f$  are variables repre-

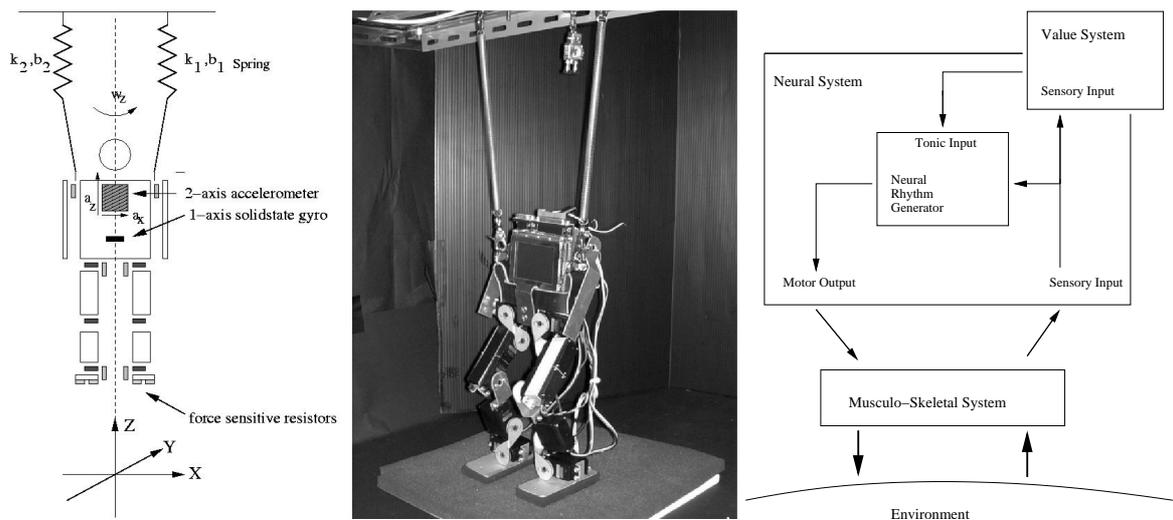


Figure 1: Left: Schematic representation of the robotic setup. Middle: Humanoid robot used in our experiments. Right: Model of neuro-musculo-skeletal system.

sensing the degree of adaptation or self-inhibition of the extensor and flexor neurons, and  $te$  is an external tonic excitation signal.  $\beta$  is an adaptation constant,  $\omega_c$  is a coupling constant that controls the mutual inhibition of neurons  $e$  and  $f$ ,  $\tau_u$  and  $\tau_v$  are time constants of the neurons' inner states and determine the strength of the adaptation effect. Sensory feedback to the pattern generator  $F_{eed}$  occurred through the four sensors located under the robot's soles. Its value was computed as the sum of the sensed ground reaction forces, and was weighted by the variable  $\omega_p$ . The operators  $[x]^+$  and  $[x]^-$  return the positive (respectively negative) part of  $x$ . The output  $y_{out}$  of the oscillator served as set-position of the respective joint.

Appropriate joint synergies among ipsilateral joints, i.e., phase relationships between the corresponding neural oscillators, were produced by feeding the flexor unit of one oscillator with a combination of the output of the extensor and flexor units of the other oscillator. Mathematically, it boiled down to adding the factor  $-\omega_s([u_e]^+ + [u_f]^-)$  to the term  $\tau_u \dot{u}_f$ , where  $\omega_s$  is an intersegmental coupling constant determining the strength of the coupling. More specifically, the knee and ankle flexor neuron were fed by the output of the ipsilateral extensor and flexor neurons of the hip joint.

#### 4. Experiments and Discussion

For the modeling and the analysis of the results, we made the assumption of an ideal mass-spring-damper system. The differential equation governing the free

oscillation of an ideal mass-spring-damper system is  $m\ddot{x} + b\dot{x} + kx = 0$ , where  $m$  is the mass of the robot, and  $b$  and  $k$  are respectively the damping coefficient and the spring constant of the spring. This equation has solutions of the form:  $x(t) = A e^{-bt/2m} \cos(\omega_d t + \phi)$ , where  $A$  and  $\phi$  are determined by the initial displacement and velocity of the robot and  $\omega_d = \sqrt{k/m - (b/2m)^2}$ . The mass of the robot (fixed throughout all experiments) was  $m = 1.33\text{kg}$ , the spring constant, which was determined empirically, amounted to  $k = 25.5\text{N/m}$  ( $k_1 = k_2 = k$  in Fig. 1 left). The damping coefficient of the spring was approximately  $b = 0.065\text{kg/sec}$  ( $b$  was computed by assuming a viscous frictional force, proportional to the velocity of the oscillation, and opposed to the direction of oscillation).

In the remainder of this section, we describe and discuss four experiments. In all experiments, the movements of the system, consisting of robot, harness and springs, were analyzed via the recording of colored markers placed on the robot's hip, knee, and ankle. The organization of the experiments reflects the complexity of their environmental interactions (with/without ground contact, with/without sensory feedback). Experiment 1 served to assess the basic properties of the real system and of the corresponding mass-spring-damper model. The goal of Experiment 2 was to understand if, and what sort of, oscillations could be sustained as a result of the interaction of the freely oscillating and kicking robot with the two springs. Experiment 3 assessed the effect of ground contact (another type of nonlinear perturbation) on the motion observed in Experiment 2, and finally, in Experiment 4, we took

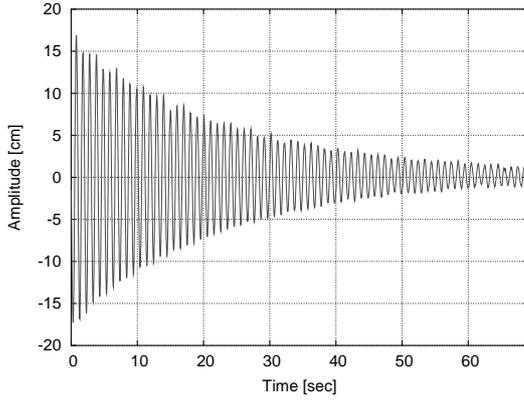


Figure 2: Damped harmonic oscillation. Plot of the displacement of the hip joint relative to its resting position. The unit of the vertical axis is *cm*, whereas the one of the horizontal axis is *sec*.

into account the sensory feedback coming from the load-sensitive sensors located under the robot's feet. In Experiments 2,3 and 4, the kicking patterns were characterized by a tight coupling between the joints, i.e., the intersegmental coupling constant was set to  $\omega_s = 0.75$ .

#### 4.1. Experiment 1 – Free oscillations

The robot was not actuated, and after an initial arbitrary vertical displacement and a zero velocity, was let oscillate freely. At the onset of the experimental session, we made sure that the robot's feet could not touch the ground. The resulting motion was harmonic and underdamped (see Fig. 2), with an exponentially decreasing amplitude of the form  $e^{-\alpha t} \sin(2\pi t/T)$ , a decay coefficient  $\alpha = 0.124/sec$ , and a period  $T = 1.01sec$ . Hence, the resonance frequency of the system could be estimated to be  $f_R = 1/T = 0.99Hz$ . To account for unevenly sampled data, this estimation was computed with an algorithm developed by Lomb [22]. The effective spring constant of the system was  $K_{eff} = 50.5N/m$  and amounted to almost twice the spring constant of each single spring. The effective damping coefficient was approximately  $B_{eff} = 0.33Nsec/m$ . Note that  $B_{eff}$  is not twice the damping coefficient of a single linear spring, as might be inferred by the value of  $K_{eff}$ . This is a clear indication of the fact that the system is not a *close-to-ideal* mass-spring system, and that a more rigorous approach would have to consider a better model for the damping force. For instance, viscous frictional forces proportional to the square of the velocity of the mass should be taken into account.

#### 4.2. Experiment 2 – Forced oscillations without ground contact

In this experiment, the robot's joints were actuated, i.e., the right-hand side term in the equation describing the motion of the robot was not 0, but (as suggested by Goldfield et al. [15]) a term  $F(t)$ , function of the parameter settings of the neural oscillators, and of the amplitude of the robot's limb movements. In

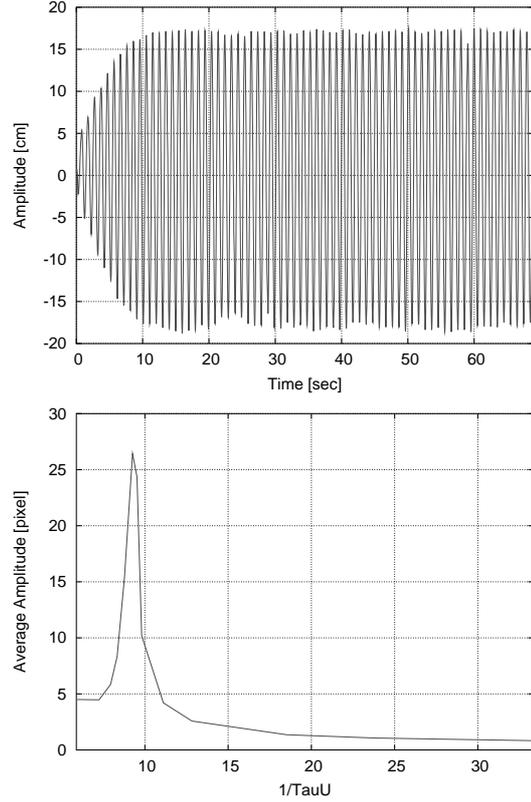


Figure 3: Forced harmonic oscillations without ground contact. Top, plot of the vertical displacement of the hip joint in *cm* (y-axis) relative to its resting position. Bottom, average of the hip displacement as a function of  $1/\tau_u$ . The peak corresponds to  $1/\tau_u = 9.26$ . The oscillation frequency is  $f_{Hip} = 1.01Hz$ , which is very close to the resonance frequency of the system  $f_R = 0.99Hz$ .

other words, the movement of the robot can be modeled as a forced mass-spring system, and the robot's kicking movements represent the driving force. As in Experiment 1, the robot could not touch the ground with its feet. After an initial transient, the oscillating system reached steady state, and oscillated with forced harmonic motion. Vertical resonance was achieved for the parameter setting  $(T_u, T_v) = (0.108, 0.216)$ , and resulted in an average vertical displacement from the rest position of  $10.6cm$ , and a peak displacements ex-

ceeding  $17\text{cm}$  – see Figure 3 (top). The dominant frequency of the oscillation, estimated via a spectral analysis of the vertical component of the hip marker position, was  $f_{Hip} = 1.01\text{Hz}$ , which was very close to the previously estimated resonant frequency of the system  $f_R = 0.99\text{Hz}$ . Interestingly<sup>1</sup>, the system displayed at least three oscillatory modes. Apart from the aforementioned vertical oscillations, for parameter settings close to  $(T_u, T_v) = (0.066, 0.132)$ , the system showed a strong horizontal oscillatory motion, whereas for  $T_u > 0.150$  and  $T_v > 0.300$ , there was an evident torsional movement. For  $T_u < 0.06$ , there were essentially no vertical oscillations – see Figure 3 (bottom).

#### 4.3. Experiment 3 – Forced oscillations with ground contact ( $\omega_p = 0$ )

The goal of this set of experiments was to assess the effect of ground contact on the oscillatory movement observed in Experiment 2. At the onset of each experiment, we made sure that the robot’s feet could touch the ground (made of a compliant material, i.e., polyurethane). The introduction of this additional nonlinear perturbation lead (given appropriate control parameters) to the emergence of a new behavioral form – *bouncing*. The result of three different parameter configurations can be seen in Figure 4. A suitable model of the movement of the robot’s center of mass would also have to take into account the nonlinear interaction with the ground, and the stiffness and damping characteristics of the floor and the feet. We suggest the following linear model (inspired by Goldfield [15]):  $m\ddot{x} + B_{eff}\dot{x} + K_{eff}x = F(t)$ , where  $F(t) = 0$  when the feet are off the ground and  $F(t) = F_0 - F_0\sin(2\pi ft)$ , when the feet are on the ground ( $F_0 > 0$ ). The effective spring constant  $K_{eff}$ , respectively the effective damping coefficient  $B_{eff}$ , incorporate the effect of springs, feet and floor.

#### 4.4. Experiment 4 – Forced oscillations with ground contact ( $\omega_p > 0$ )

The sensory feedback and the contact with the ground induced – in Goldfield’s words [15] – a “haptic closing of the loop”, and turned the *linear and externally driven mass-spring system* of Experiment 2 and 3, into an *autonomous limit-cycle system* with the intrinsic timing determined by the moment of foot contact with the ground, and the gain of the feedback connection  $\omega_p$ . In other words, the frequency of the kicking (im-

<sup>1</sup>Goldfield [3] reported that a characteristic of spontaneous activity in infants is that it enters preferred stable states and exhibits abrupt phase transitions between these states.

PLICITLY timed by the neural oscillators) and its phase relationship with the bouncing, was regulated by the haptic information, and resulted in an entrainment effect between ground contact, and neural oscillators. A positive  $\omega_p$  had at least two advantages: *stabilized*

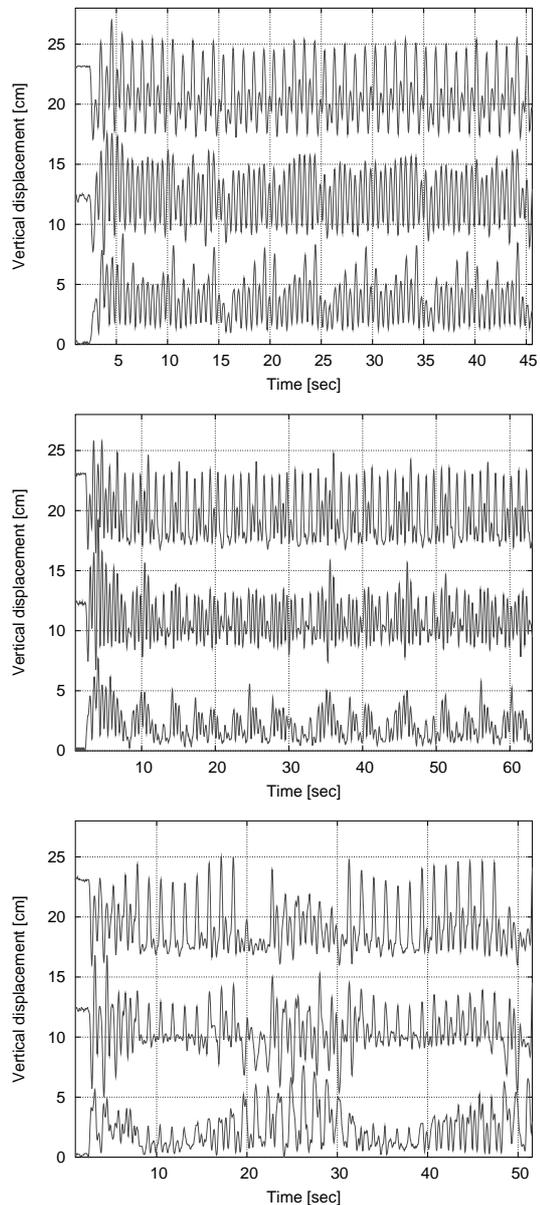


Figure 4: Forced harmonic oscillations with ground contact (bouncing) in the case of  $\omega_p = 0$ .  $T_u = 0.108, T_v = 0.216$  (top),  $T_u = 0.114, T_v = 0.228$  (center), and  $T_u = 0.140, T_v = 0.280$  (bottom). In all graphs, from bottom to top, the three curves represent the vertical displacement of the ankle, knee and hip marker in  $\text{cm}$ . The dominant frequency for the hip position in the top plot is  $f_{Hip} = 1.01\text{Hz}$ ,  $f_{Hip} = 0.95\text{Hz}$  for the middle plot, and  $f_{Hip} = 0.73\text{Hz}$  for the bottom plot.

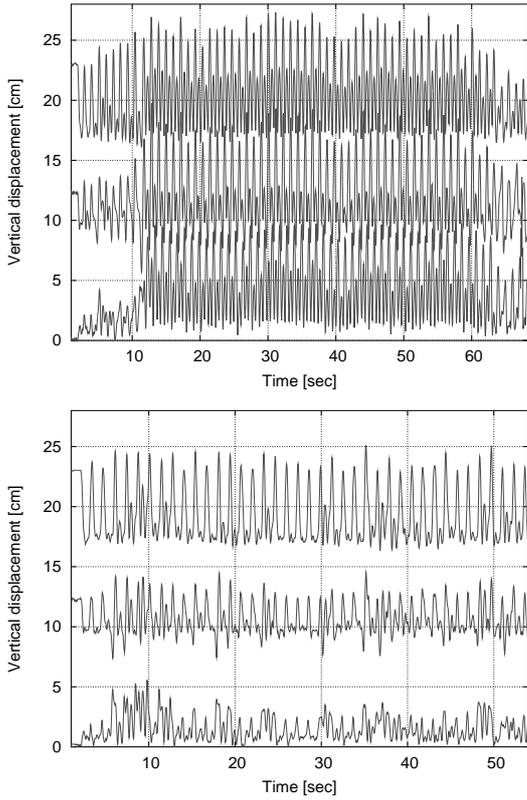


Figure 5: Forced harmonic oscillations with ground contact (bouncing) in the case of  $T_u = 0.114, T_v = 0.228, \omega_p = 0.5$  (top) and  $T_u = 0.140, T_v = 0.280, \omega_p = 0.75$  (bottom). In both graphs, from bottom to top, the three curves represent the vertical displacement of the ankle, knee and hip marker in *cm*.

and sustained bouncing, as well as an increase of its amplitude (measured as difference between successive maximum and minimum of the vertical displacement). This can be seen in Figure 5. In the top graph, the parameter configuration was  $(T_u, T_v) = (0.114, 0.228)$  and the gain of the feedback connection  $\omega_p = 0.5$ . The dominant frequency of the vertical oscillation (determined via a spectral analysis of the hip marker) was  $f_{Hip} = 0.93Hz$  (for the same parameter configuration, but with  $\omega_p = 0$  and  $f_{Hip} = 0.95Hz$ ). The maximum vertical displacement of the hip relative to the initial position of the ankle marker was  $27.3cm$ , whereas its maximum vertical displacement relative to the initial position of the hip marker was  $4.4cm$ . The effect of the absence of sensory feedback, i.e.,  $\omega_p = 0$ , can be appreciated by comparing Figure 5 (top) with Figure 4 (center). After a short initial transient, the robot settled into a stable oscillatory movement, but did not bounce. The plot on the bottom of Figure 4 and Figure 5 show the stabilizing effects of sensory feedback. In both

cases, the parameters were  $T_u = 0.140$  and  $T_v = 0.280$ . For  $\omega_p = 0.75$ , the bouncing was stable and sustained, whereas for  $\omega_p = 0$ , the bouncing suddenly collapsed (more variability). In this case, the model is more complicated and needs to take into account the change of phase and timing due to the sensory feedback. This is realized with the introduction of a new variable  $\phi$ :  $m\ddot{x} + B_{eff}\dot{x} + K_{eff}x = F(t, \phi)$ .

#### 4.5. Further Discussion

Our premise of a tight synergy between hip, knee and ankle joints, i.e., the fact that the intersegmental coupling constant  $\omega_s$  was fixed to 0.75 throughout the whole study, finds justification in developmental psychology. Findings reported in [14] show a high degree of coordination between the hip, knee and ankle joints of the same leg (intra limb coordination) in infants younger than 12 months. According to the same authors, *kicking* appears to be an especially well-coordinated movement, quite distinct from other less rhythmic movements. After the first month of life, infants begin to use kicks for task-related ends. As mentioned previously, we believe that this tight synchrony, while reducing the movement complexity, could help decreasing the complexity of the control structure and could bootstrap and speed up the dynamical self-organization of movement patterns. This strong joint synchrony can be considered as an example of reduced variability in the young infant [23]. As learning progresses, the tight intersegmental coupling could be loosened, and more complex spatiotemporal patterns could be explored. Eventually, as a result of this self-exploration, movement pattern, which exploit passive forces and harness natural dynamics could emerge.

The rhythmic nature of the task (oscillating or bouncing), which can be interpreted as a form of circular reaction<sup>2</sup>, and the flexibility in the selection of both, morphological and neural control parameter, may facilitate the process of self-exploration. As a matter of fact, rhythmic (not necessarily task-oriented) activity is highly characteristic of emerging skills during the first year of life. Thelen and Smith [14] suggested that oscillations are the product of a motor system under emergent control, i.e., when infants attain some degree of intentional control of their limbs or body postures, but when their movements are not fully goal-corrected.

<sup>2</sup>Circular reactions represent an essential sensorimotor stage of Piaget's developmental schedule [9]. They refer to the repetition of an activity in which the body starts in one configuration, goes through a series of intermediate stages, and eventually returns to the initial configuration.

To produce rhythmic activity, we employed a neural structure generally referred to as central pattern generator. As a demonstration that sensory feedback is not necessary for the generation and coordination of such movements, experiments in completely isolated spinal cords and in animals without sensory feedback, have shown that the patterns generated by these type of structures are very similar to those recorded in not deafferented, i.e., intact, animals [24]. On the other hand, the question of how sensory feedback interacts with the central pattern generator is still open [12]. What emerged from our study is that sensory feedback induces a reduction of movement variability, an increase of bouncing amplitude, and leads to stability. A similar finding, in the case of biped walking, is reported by Taga [13] who states that, through a recurrent interaction of sensory information and movement generation, *the instability of the human body is stabilized as a limit cycle*.

## 5. Conclusion and Future Work

In [15], Goldfield suggests that two processes are involved in the developmental transformation of spontaneous activity into a task-specific action pattern: *assembly* and *tuning*. While *assembly* refers to the self-organization of relationships between the components of the system, *tuning* refers to the adaptation of the parameters of the system to particular conditions. In this paper, we have primarily focussed on the *tuning* phase by assuming a meaningful result of the *assembly* phase, namely, a task-specific and strong synergy between the joints involved in the bouncing process.

With respect to the *tuning* phase, there is still much to do. Two processes should be considered: (a) in some sense, *tuning* could refer to the non-stationary regime which occurs before stabilization of the pattern. In other words, it would be a by-product of the entrainment between control structures and environment – when sensory feedback turns the system into an *autonomous limit-cycle system*; (b) at a lower level of control, *tuning* could also be implemented as changes in gain or time-constants of the neural oscillators. In this respect, future work will involve the local exploration of control parameters using a mechanism of Boltzmann exploration driven by a value system (see Fig. 1 right). The authors have successfully used this combination in a pendulating humanoid robot [18].

The issue of the mechanisms underlying the *assembly* phase is very interesting. Though bouncing is intrinsically a rhythmic activity for which central pattern generators are very suitable, there is no evidence that newborn infants immediately use their limbs in a man-

ner consistent with the output of central pattern generators, and indeed, kicking movements are more plausible candidates. Given that neural oscillators are usually modeled as a set of mutually inhibitory neurons, the *assembly* phase could consist of a process whereby the topology of a vanilla-type cell assembly is changed over time, upon feedback from the environment, and driven by a value system (based on amplitude of the oscillations for instance).

Yet, this may not be sufficient to hypothesize a valid model of child development as there is evidence that kicking behaviors show patterns, in space, and in time. In particular, Taga recently discussed the chaotic dynamics of spontaneous movements in human infants [25]. Thus, formulating the development of those skills in a dynamical systems framework would be highly desirable so that an appropriate set of adaptive mechanisms could be implemented and tested against human data. A single instance of such mechanism, which has been extensively studied by Taga [12, 13] in human infants, and by the authors [18, 26] in a robotic system, is the alternate cycle of freezing and freeing of degrees of freedom.

## References

- [1] E.J. Gibson. Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annual Review of Psychology*, 39:1–41, 1988.
- [2] E.M. Bushnell and J.P. Boudreau. Motor development in the mind: The potential role of motor abilities as a determinant of perceptual development. *Child Development*, 64:1005–1021, 1993.
- [3] E.C. Goldfield. *Emergent Forms: Origins and Early Development of Human Action and Perception*. Oxford University Press, New York, USA, 1995.
- [4] A.W. Smitsman and R. Schellingerhout. Exploratory behavior in blind infants: How to improve touch? *Infant Behavior and Development*, 23:485–511, 2000.
- [5] L. Berthouze and A. Tijsseling. Embodiment is meaningless without adequate neural dynamics. 2001.
- [6] K. Schneider, R.F. Zernicke, B. Ulrich, J. Jensen, and E. Thelen. Understanding movement control in infants through the analysis of limb inter-segmental dynamics. *Journal of Motor Behavior*, 22:493–520, 1990.

- [7] K. Schneider and R.F. Zernicke. Mass, center of mass, and moment of inertia estimates for infant limb segments. *Journal of Biomechanics*, 25:145–148, 1992.
- [8] R.M. Angulo-Kinzler. Exploration and selection of intralimb coordination patterns in 3-month-old infants. *J. of Motor Behavior*, 33(4):363–376, 2001.
- [9] J. Piaget. *The Origins of Intelligence*. Routledge: New York, USA, 1953.
- [10] C. Von Hofsten. Prospective control: A basic aspect of action development. *Human Development*, (36):253–270, 1991.
- [11] J.A.S. Kelso and B.A. Kay. Information and control: A macroscopic analysis of perception-action coupling. In H.Heuer and A.Sanders, editors, *Perspectives on perception and action*, pages 3–32, 1987.
- [12] G. Taga. Self-organized control of bipedal locomotion by neural oscillators in unpredictable environments. *Biological Cybernetics*, 65:147–159, 1991.
- [13] G. Taga. A model of the neuro-musculo-skeletal system for human locomotion. *Biological Cybernetics*, 73:113–121, 1995.
- [14] E. Thelen and L. Smith. *A Dynamic Systems Approach to the Development of Cognition and Action*. MIT Press, Cambridge, Mass., USA. A Bradford Book, 1994.
- [15] E.C. Goldfield, B.A. Kay, and W.H. Warren. Infant bouncing: the assembly and tuning of an action system. *Child Development*, 64:1128–1142, 1993.
- [16] E. Thelen, D.M. Fisher, and Ridley-Johnson. The relationship between physical growth and a newborn reflex. *Infant Behavior and Development*, 7:479–493, 1984.
- [17] B. Vereijken, R.E.A. van Emmerik, H.T.A. Whiting, and K.M. Newell. Free(z)ing degrees of freedom in skill acquisition. *J. of Motor Behaviour*, (24):133–142, 1992.
- [18] M. Lungarella and L. Berthouze. On the interplay between morphological, neural and environmental dynamics: A robotic case-study. *Adaptive Behavior (Special Issue)*, 10, 2002. in press.
- [19] S.J.A. Kelso. *Dynamic Patterns*. Cambridge, MA: MIT Press. A Bradford Book, 1995.
- [20] K. Matsuoka. Sustained oscillations generated by mutually inhibiting neurons with adaptation. *Biological Cybernetics*, 52:367–376, 1985.
- [21] S. Grillner. Neurobiological bases on rhythmic motor acts in vertebrates. *Science*, pages 143–149, 1985.
- [22] N.R. Lomb. Least-squares frequency analysis of unevenly spaced data. *Astrophysics and Space Science*, 39:447–462, 1976.
- [23] J.P. Piek. The role of variability in early development. *Infant Behavior and Development*, 156:1–14, 2002.
- [24] A. Ijspeert. Vertebrate locomotion. In M.Arbib, editor, *The Handbook of Brain Theory and Neural Networks*. Bradford Book, 2002.
- [25] G. Taga, R. Takaya, and Y. Konishi. Analysis of general movements of infants towards understanding of developmental principle for motor control. In *Proc. of 1999 IEEE Int. Conf. on Systems, Man, and Cybernetics*, pages 678–683, 1999.
- [26] M. Lungarella and L. Berthouze. Adaptivity via alternate freeing and freezing of degrees of freedom. In *Proc. of the 9th Int. Conf. on Neural Information Processing*, pages 482–487, 2002.