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Motor Skill Acquisition Under Environmental Perturbations: On the Necessity of Alternate Freezing and Freeing of Degrees of Freedom

Luc Berthouze, Max Lungarella
Neuroscience Research Institute, Tsukuba, Japan

In a recent study on the pendulation of a small-sized humanoid robot (Lungarella & Berthouze, 2002a,b), we provided experimental evidence that starting with fewer degrees of freedom enables a more efficient exploration of the sensorimotor space during the acquisition of a task. The study came as support for the well-established framework of Bernstein (1967), namely that of an initial freezing of the distal degrees of freedom, followed by their progressive release and the exploitation of environmental and body dynamics. In this paper, we revisit our study by introducing a nonlinear coupling between environment and system. Under otherwise unchanged experimental conditions, we show that a single phase of freezing and subsequent freeing of degrees of freedom is not sufficient to achieve optimal performance, and instead, alternate freezing and freeing of degrees of freedom is required. The interest of this result is twofold: (1) it confirms the recent observation by Newell & Vaillancourt (2001) that Bernstein's (1967) framework may be too narrow to account for real data; (2) it suggests that perturbations that push the system outside its postural stability or increase the task complexity may be the mechanism that triggers alternate freezing and freeing of degrees of freedom.

Keywords developmental robotics · embodiment · neural oscillator · freezing and freeing of degrees of freedom · entrainment

1 Introduction

Body-related morphological changes during the early stages of infancy, either slow and irreversible modifications (such as physical growth), or relatively rapid, task-related re-organizations of the musculo-skeletal system (such as the transition from crawling to standing), are a salient characteristic of the ongoing developmental process. In this paper, we focus on the effect on behavior of one particular form of morphological change: the release of constraints in the motor system. A few telling examples of constraints in the sensory,

motor, and neural systems of vertebrate species such as rats, cats, and humans are the immaturity of the accommodative system (Turkewitz & Kenny, 1982), the low acuity of vision and absence of binocularity (Hainline, 1998), the low leg muscle:leg fat ratio, and the poor postural control of head, trunk, arms, and legs (Thelen & Smith, 1994; Bertenthal & Von Hofsten, 1998). Studies in developmental psychology have shown that constraints in the sensory system, and biases in the motor system and their subsequent release, may play a pivotal role in the ontogeny of motor skills and in shaping the infant's exploratory behavior

Correspondence to: L. Berthouze, Neuroscience Research Institute (AIST), Tsukuba AIST Central 2, Umezono 1-1-1, Tsukuba 305-8568, Japan. *E-mail*: Luc.Berthouze@aist.go.jp, *Tel*.: +81-298-615369, *Fax*: +81-298-615841

(Turkewitz & Kenny, 1982; Harris, 1983; Thelen, Fisher, & Ridley-Johnson, 1984; Bushnell & Boudreau, 1993; Goldfield, 1995; Piek, 2002).

In this paper, we consider the morphological limitations in the motor apparatus of a developing system as particular instances of ontogenetic adaptations, that is, neurobehavioral traits of an immature organism with a specific adaptive role at a particular stage of development (Bjorklund & Green, 1992). We make the premise that appropriate initial constraints on morphological resources are not only beneficial to the emergence of stable sensorimotor patterns with an increased tolerance to environmental perturbations, but help also to bootstrap later stages of learning and development.

The study of morphological changes is an important area of research. Yet, they have been largely neglected by biologically motivated robotics research, presumably because of: (1) the difficulties involved with the actual implementation of the suggested morphological changes in real-world systems (as opposed to simulated systems in which morphological changes can be achieved relatively easily); and (2) the lack of proper means for quantifying their effects on neural dynamics and behavior.

Recently, the robotics community has started to address the former issue. The ultimate goal is to create machines that by changing their morphology (shape) are able to perform various tasks in various environments. Examples are the self-reconfigurable modular robots built by Murata, Yoshida, Kurokawa, Tomita, & Kokaji (2001) and the morpho-functional machine initiative promoted by Hara, & Pfeifer (2003). In both instances, change of shape is concerned with the functionality of the machine, and not with learning mechanisms. The quantification of movements has also been investigated, and a few methods have been proposed. Dimensional analysis, for instance, gives an index of the number of independent degrees of freedom required to produce the time series of a particular movement (Kay, 1988; Mitra, Amazeen, & Turvey, 1998). The spatio-temporal organization of the joint-space data associated with a movement can also be captured by principal component analysis. Haken (1996) showed that early in the learning of a "pedalo task" (a skating locomotion task in which both skates are connected by a rigid link that constrains their relative motion to a cycloidal trajectory in the vertical plane) several principal components were necessary to explain most of the variance of the data, and that after practice, this number of significant principal components collapsed to one. Although useful for a descriptive characterization of the system, both types of analysis do not provide any information on the mechanisms underlying the described learning process.

More central to the theme of this paper is the "degrees of freedom problem", first pointed out by Bernstein (1967; see also Vereijken, van Emmerik, Whiting, & Newell, 1992; Sporns & Edelman, 1993; Zernicke, & Sneider, 1993; Newell & Vaillancourt, 2001). Although the human musculo-skeletal apparatus is a highly complex and nonlinear system, with a large number of potentially redundant degrees of freedom (e.g., more than one motor signal can lead to the same trajectory), well-coordinated and precisely controlled movements emerge. In reality, the redundancy increases at the level of the muscles (there are many more muscles than joints), and explodes at the neural level. While it guarantees flexibility and adaptability (think of the hand's astounding manipulative abilities, for instance), it also challenges the control of body movements, largely because of the enormous number of components involved in the generation and coordination of a movement. A possible solution to the control issues raised by the excess number of degrees of freedom was suggested by Bernstein himself. His proposal is characterized by three stages of change in the number of degrees of freedom that accompany motor learning and development. Initially, in learning a new skill or movement, the peripheral degrees of freedom (the ones farther from the trunk, such as wrist, and ankle) are reduced to a minimum (freezing). Subsequently, as a consequence of experiment and exercise, restrictions at the periphery are gradually lifted (freeing), until *all* degrees of freedom are incorporated. Eventually, reactive phenomena (such as gravity and passive dynamics) are exploited, and the most efficient movements are selected. Several studies have provided evidence for *particular features* of Bernstein's three-stage model. Vereijken et al. (1992), for example, conducted an empirical test of the related issues of freezing and freeing degrees of freedom in adults learning a ski-simulator task. The kinematic analysis of the limb and torso motions showed that at the outset of learning, subjects froze many of the joint segments of the whole body. With subsequent practice, subjects introduced active motion at the ankle, knee, and hip joints in a fashion consistent with the freeing of (release of the ban on) degrees of freedom.

Other investigations included the learning by adults of a handwriting signature with the non-dominant limb (Newell & van Emmerick, 1989), a dart-throwing task (McDonald, Emmerik, & Newell, 1989), pistol shooting (Arutyunyan, Gurfinkel, & Mirskii, 1969), and the development of infant leg kicking between 2 weeks and 7 months of age (Jensen, Thelen, Ulrich, Schneider, & Zernicke, 1995).

In this study, we approach the "degrees of freedom problem" by employing a robot-based synthetic modeling that exploits findings from developmental psychology. Some instances of a developmental approach to the issue have already been reported (Berthouze & Kuniyoshi, 1998; Lungarella & Berthouze, 2002b; Metta, 2000; for review, see Lungarella & Berthouze, 2002b). Those studies, however, framed the role of the freezing of degrees of freedom, and their subsequent freeing, in an information-processing context—similar to existing connectionist learning techniques, such as constrained or incremental learning (e.g., Elman, 1993). More in line with our ideas, Taga (1997) 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, he was able to reproduce (in simulation) the *U-shaped* developmental trajectory of infants' stepping movements during which reflexive movement patterns first appear, then disappear, and months later reappear in altered form. His result was in agreement with Bernstein's three-stage model of skill acquisition, and thus, he hypothesized that a *developmental* mechanism of freezing and freeing may be important for learning stable and complex movements. In this paper, however, we will challenge this model by showing that in the presence of strong couplings between system and environment during task learning, a rigid sequence of morphological changes (freezing → freeing → selection) may not be sufficient. Instead, a more complex dynamics of changes should be considered.

2   Pendulation Study and Release of the Peripheral Degrees of Freedom

In Lungarella & Berthouze (2002b), we reported our investigation on the exploration of pendulation (or swinging) in a small-sized humanoid robot. We chose swinging as a case study, because it is a repetitive activity, and thus, characteristic of emerging skills dur-

ing the first year of life—see, for instance, the notions of circular reaction (Piaget, 1953) and body babbling (Meltzoff & Moore, 1997). Thelen, Fisher and Ridley (1984) suggested that oscillations are the product of a motor system under emergent control; that is, when infants attain some degree of intentional control of limbs or body postures, but when their movements are not fully "goal-corrected."

Assuming a neural control structure suitable for the task at hand, we proposed a comparative analysis between outright use of the full body for exploration, and progressive exploration characterized by a developmental freeing of the degrees of freedom, such as the one hypothesized by Bernstein (1967). The study produced a number of insights, which we summarize here:

- The outright use of all degrees of freedom (hip and knee) reduced the likelihood of *physical entrainment*, that is, the mutual regulation of body and environmental dynamics. We observed that small changes in the control parameters yielded different oscillatory behaviors. Moreover, even within one control parameter setting, the system displayed several rapid and abrupt transitions between different stationary regimes. This feature is characteristic of spontaneous movement activity in infants (Goldfield, 1995).
- By freezing the peripheral degree of freedom (knee), we observed an increase of the range of control parameter settings that led to stable oscillatory behaviors, as well as of the range of oscillation frequencies for which physical entrainment could effectively occur. Miyakoshi, Yamakita, & Furata (1994) and Williamson (1998) have shown that the exploitation of entrainment can indeed yield robust behavior in various tasks.
- Bootstrapped control of all degrees of freedom in which the peripheral degree of freedom was released after the system had already stabilized in a single degree of freedom (1-DOF) stationary regime, resulted in a dense distribution of parameter settings yielding stable oscillatory behaviors with a large amplitude. Statistical analysis showed that these large oscillations could not be accounted for solely by the oscillations achieved in the 1-DOF (frozen) configuration. Instead, the freezing and freeing of the degrees of freedom reduced the sensitivity of the system to the selection of particular hip–knee parameter configurations.

- The study showed that joint synergies[1] that are characteristic of human motor control (e.g., Spencer & Thelen, 1999) played a complementary role to physical entrainment during the release of the peripheral degree of freedom. A strong coupling resulted in *neural entrainment*, whereby the control frequency of the lower limb locked onto the control frequency of the upper limb. The phase locking between both limbs stabilized the oscillatory behavior, and thus by entrainment effect, also the ongoing physical entrainment. Abrupt phase transitions did not occur and transients were shortened, which is typical for task execution at the later stage of motor-skill learning (Goldfield, 1995).

3   Adding Nonlinear Perturbations

In this paper, we revisit our previous study by adding a nonlinear coupling between environment and system. Our focus is on whether a progressive release of the peripheral degrees of freedom can provide adaptivity and robustness against perturbations and constraints such as the rubber band. Both experimental setup and control architecture are identical to those used in our previous study.

The experimental setup consisted of a small-sized humanoid robot with 12 degrees of freedom. Through two thin metal bars fixed to its shoulders, the robot was attached by a passive joint to a supportive metallic frame in which it could freely oscillate in the vertical (sagittal) plane (see Figure 1). Each leg of the robot had five joints, but only two of them (hip and knee) were used in our experiments. High torque servomotors actuated each joint. Because these motors do not provide any form of sensor feedback, we used an external camera to track colored markers placed on the robot's limbs. Throughout this study, we refer to feedback as the visual position of the hip in a frame of reference centered on the hip position, when the robot is in its resting position.

To study the effect of environmental interaction during learning, we introduced an asymmetric nonlinear coupling between system and environment in the form of a thread attached to the humanoid robot at hip-level, and connected to the supportive frame via a rubber band. This flexible link was designed so that the rubber band would extend only when the
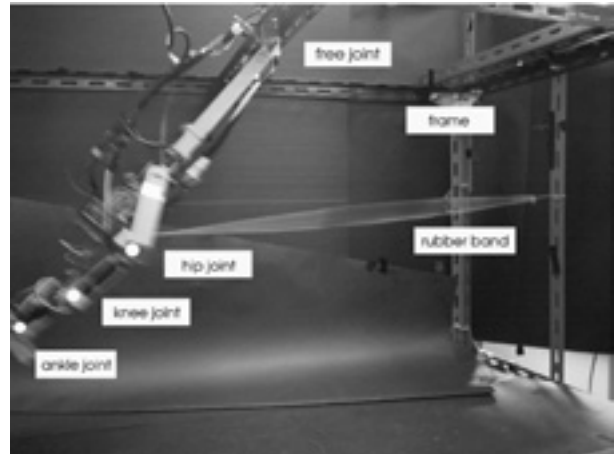

Figure 1   Humanoid robot used in our experiments.

robot was tilted backwards by at least 10°. This setting was kept constant throughout the study. The strong dampening properties of this coupling are illustrated in Figure 2, which shows the visual positions of the hip and ankle during oscillations with control parameters known to yield resonant behavior in unperturbed situations.

Figure 3 depicts the distributed architecture used to control the humanoid robot. Each limb was controlled by a separate neural oscillator. The four neural oscillators controlling the knees and hips were modeled by the following set of nonlinear differential equations, derived from Matsuoka (1985):

$$\tau_{u_f}\dot{u}_f = -u_f - \beta v_f - \omega_c[u_e]^+ - \omega_p[F_{eed}]^+ + te \quad (1)$$

$$\tau_{u_e}\dot{u}_e = -u_e - \beta v_e - \omega_c[u_f]^+ - \omega_p[F_{eed}]^- + te \quad (2)$$

$$\tau_{v_f}\dot{v}_f = -v_f + [u_f]^+ \quad (3)$$

$$\tau_{v_e}\dot{v}_e = -v_e + [u_e]^+ \quad (4)$$

where u_e and u_f are the inner states of the neuron e (extension) and f (flexor), v_e and v_f are variables representing the degree of adaptation or self-inhibition of the extensor and flexor neurons, and *te* is an external tonic excitation signal that determines the amplitude of the oscillation. β is an adaptation constant, ω_c is a coupling constant that controls the mutual inhibition of neurons e and f, and ω_p is a variable weighting the proprioceptive feedback F_{eed}. This proprioceptive feedback is obtained through the visual position of the hip
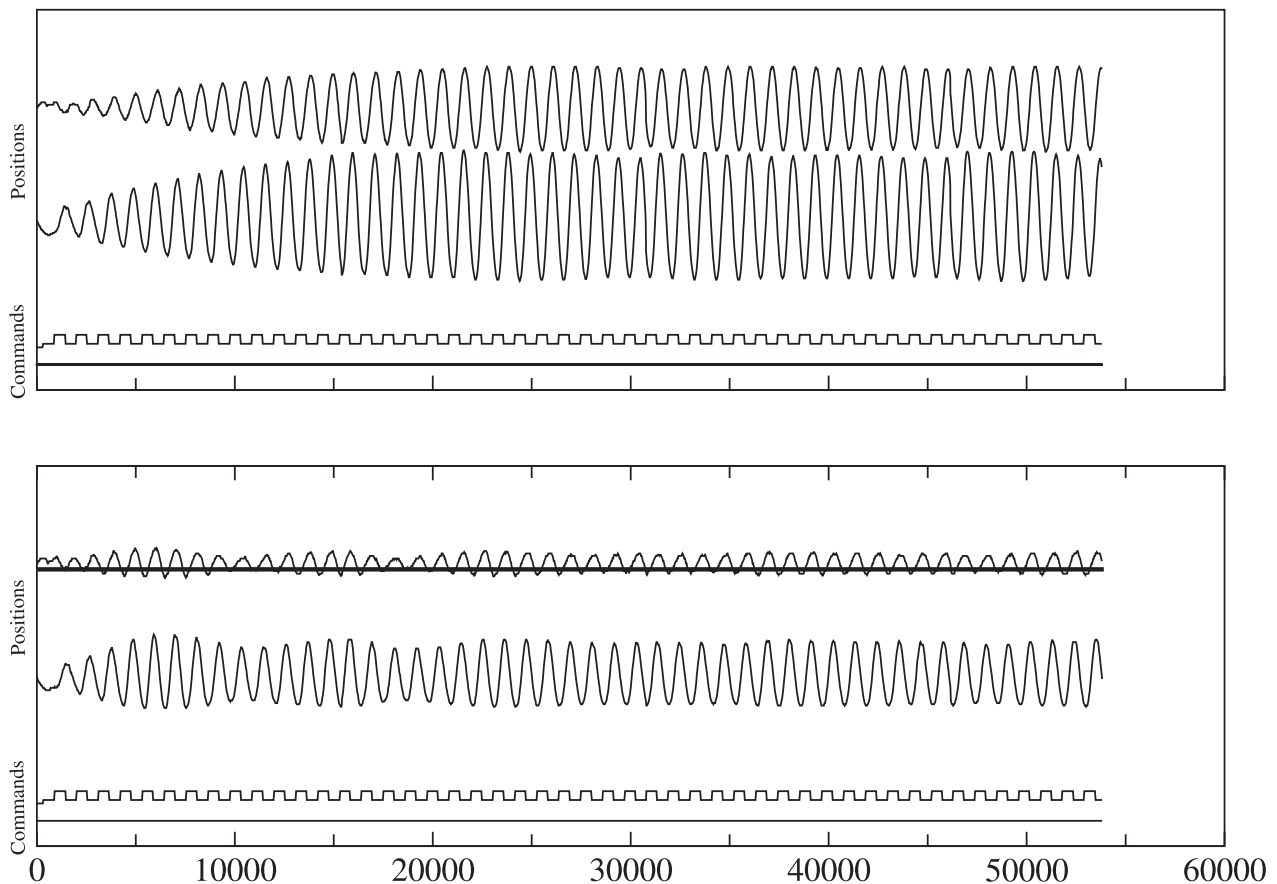
Figure 2   Resonant oscillations for ($\tau_u = 0.065$, $\tau_v = 0.6$) without perturbations (top). Resulting behavior under perturbations (bottom). In each graph, the time-series denote motor impulses (bottom), ankle position (middle) and hip position (top). In this figure, as well as all other similar figures in this paper, the vertical axis is unlabeled, because it depicts time-series of different scales and units, i.e., visual positions (pixels), motor commands (radians). 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 (ms).

in a frame of reference centered on the hip position when the robot is in its resting position. τ_u and τ_v are time constants of the neurons' inner states and determine the strength of the adaptation effect. The operators $[x]^+$ and $[x]^-$ return the positive and negative parts of x respectively.

Joint synergy between hip and knee, i.e., the appropriate phase relationship between the corresponding neural oscillators, was implemented by feeding the flexor unit of the knee oscillator with the combined outputs of the flexor and extensor units of the hip controller. A factor $-\omega_s([u_f^h]^+ + [u_e^h]^+)$ was added to the term $\tau_{u_f}\dot{u}_f$ in the flexor unit of the knee oscillator (Equation 1), with u_e^h and u_f^h the inner states of the flexor and extensor units in the hip oscillator,

and ω_s the intersegmental coupling parameter determining the strength of the coupling.

As in Taga (1991), we used each neural oscillator as a rhythm generator, with its output y given by the difference $y = u_f - u_e$ between the activities of the flexor and extensor units. This value was then fed to a pulse generator which detects sign changes in the output y of the neural oscillator and generates a pulse of constant amplitude and of sign $sgn(y)$. The angular position of the motor results from the integration in time of each pulse. Though very primitive (a variant of on–off control), this controller is a suitable approximation of the output y. Indeed, it preserves the frequency and maximal amplitude of the signal, as well as the timing of sign inversions within one period.
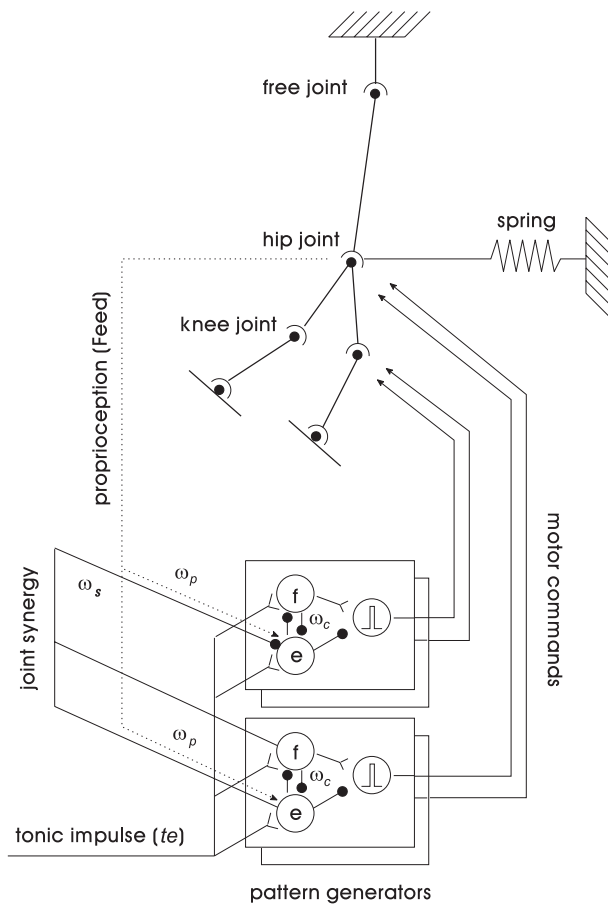
Figure 3 Schematics of the experimental system and neural control architecture. Joint synergy is only activated in experiments involving coordinated 2-degrees-of-freedom control.

As in the original study (unless specified otherwise), we did not change the following parameters throughout this study: $\beta = 2.5$, $\omega_c = 2.0$, $te = 20$ for the hip ($te = 15$ for the knee). Other parameters were set as discussed in the text.

4   Results and Discussion

4.1 Protocol

With the aim of a comparative analysis between the outright use of all degrees of freedom and a progressive release of the degrees of freedom, we realized two sets of experiments. In the first set, we considered *2-DOF exploratory control*, with each pair of hip and knee joints controlled by a separate oscillator unit and the other joints kept stiff in their reset position. We

treated two cases. In the first case, the oscillator units were independent and their respective parameter spaces were independently explored. In the second case, the oscillator units were coupled via an intersegmental coupling parameter ω_s, with the goal of realizing neural entrainment between oscillatory units. In the second set of experiments, we considered a *bootstrapping 1-DOF exploratory phase* during which only the hip joint was controlled, while other joints were kept stiff in their reset position. When a stationary regime was obtained, the peripheral degree of freedom (knee) was released and controlled by its own oscillator unit. The robot's movements were analyzed via the recording of the hip, knee, and ankle positions. The same initial conditions were used in all experiments, with the humanoid robot starting from its resting position. We only considered parameter configurations that yielded motion without external intervention.

4.2 Experimental Observations

Unless specified otherwise, all experiments within each scenario were found to yield qualitatively similar results in terms of the characteristics of the oscillatory behavior, with variations accounted for by differences in initial conditions. For practical reasons (excessive strain on the physical structure of the robot as well as on the servo-motors), we did not conduct sufficient runs to establish statistically meaningful results between scenarios.

4.2.1 Selection of Suitable Hip-Control Parameters in 1-Degree-of-Freedom Exploratory Control   Because an exhaustive exploration of the parameter space for two independent neural controllers was not feasible, we performed a preliminary exploration of the hip oscillator's parameter space in a 1-DOF configuration (the reader should refer to Figure 4 and Table 1 for an overview of the different configurations discussed in the following paragraphs). We conducted this exploration using the value-based exploration algorithm presented in the first study (Lungarella & Berthouze, 2002b) and summarized in the Appendix. This exploration essentially confirmed our previous findings. Adaptivity to external perturbations and optimal task performance, i.e., oscillations with large amplitude, required fine-tuning of the parameters. Although the hip–ankle phase plots were not necessarily stationary,
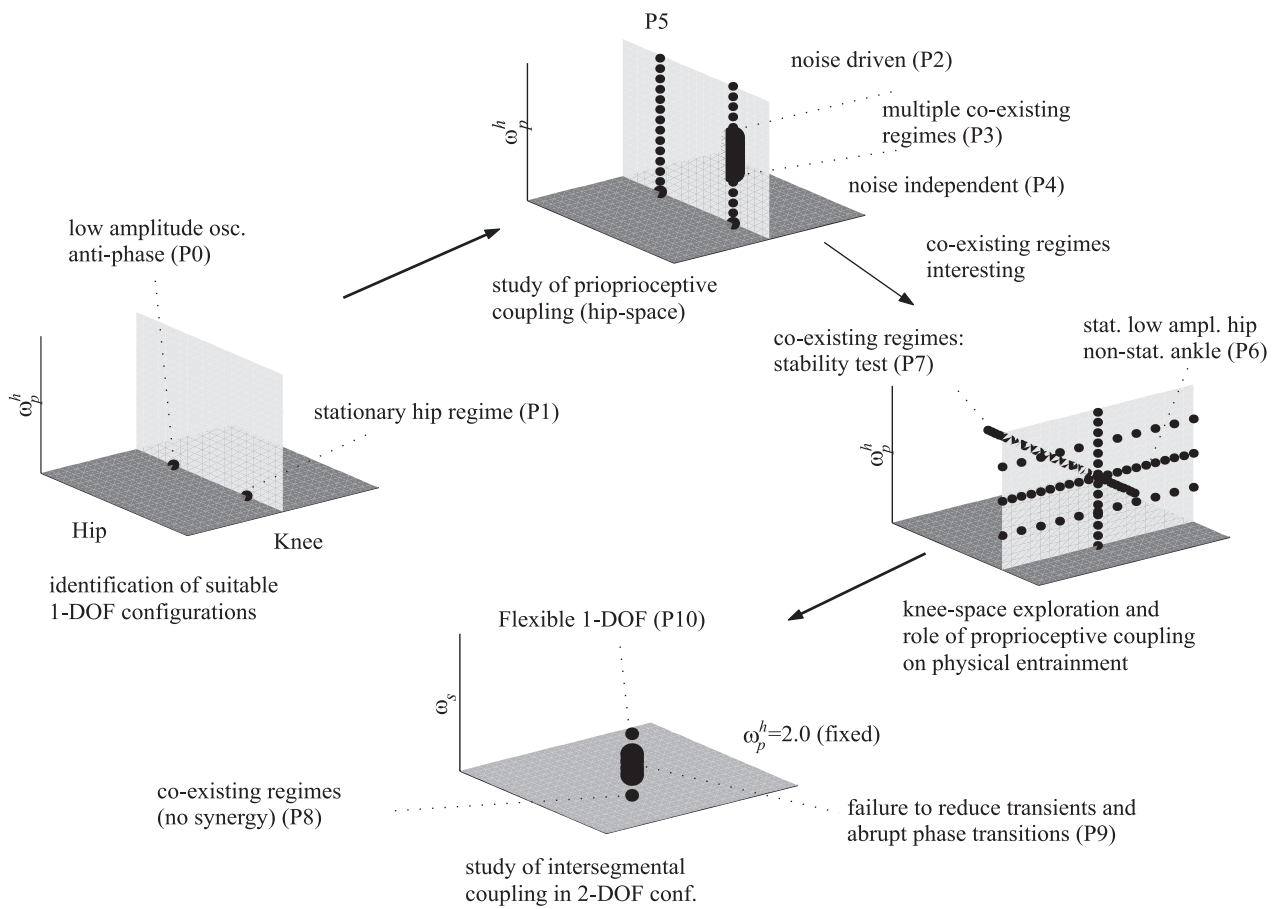
Figure 4   Flow of the proposed experimental discussion with respect to both 1-degree-of-freedom (DOF) and 2-DOF exploration.

Table 1   Synopsis of the control parameter settings used in Figure 4.

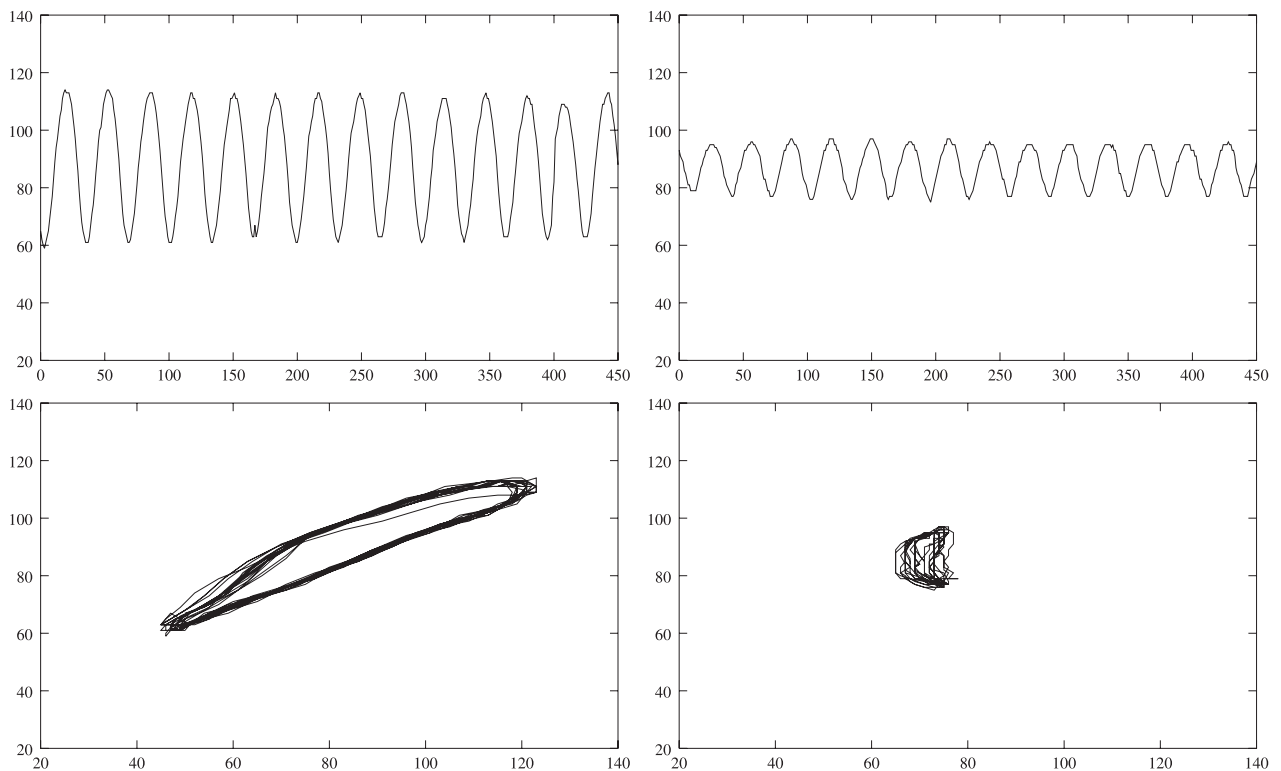| Label	τ_u^h, τ_v^h	τ_u^k, τ_u^k	ω_p^h	ω_s
P0	0.035, 0.65		0.0	
P1	0.060, 0.65		0.0	
P2	0.060, 0.65		[3.0,7.0]	
P3	0.060, 0.65		[2.0,3.0]	
P4	0.060, 0.65		[0.0,2.0]	
P5	0.035, 0.65		[0.0,7.0]	
P6	0.060, 0.65	[0.020,0.090], [0.35,0.80]	2.0	
P7	[0.025,0.075], 0.65		2.0	
P8	0.060, 0.65	0.035, 0.40	2.0	0.0
P9	0.060, 0.65	0.035, 0.40	2.0	[0.25,0.75]
P10	0.060, 0.65	0.035, 0.40	2.0	1.0

Figure 5 Time-series of hip position (top) and ankle-hip phase plots (bottom) for ω_p^h = 0.25 (left) and ω_p^h = 4.0 (right). The oscillator time-constants are: τ_u = 0.035, τ_v = 0.65 in both cases. In the upper row of plots, the vertical axis denotes the visual positions of the ankle (left) and the hip (right). The horizontal axis denotes time (ms). In the lower row of plots, both vertical and horizontal axes correspond to the visual positions of the hip (left plot) and ankle (right plot) (pixels).

all configurations led to a stationary regime of hip oscillations. Two settings were of particular interest, and were used to carry out the experiments described in this paper: (τ_u = 0.035, τ_v = 0.65) and (τ_u = 0.06, τ_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.

The first setting (τ_u = 0.035, τ_v = 0.65) was characterized by low-amplitude (23 units) antiphase oscillations of the legs with respect to body motion. Antiphase oscillations are indicated by a phase difference between the vertical components of the hip and ankle positions equal to π radians. A transversal analysis along the proprioceptive gain $\omega_p^h \in [0.0, 7.0]$ showed that all experiments yielded a stationary regime, robust to external perturbations such as a manual push. With a very weak proprioceptive gain, i.e., $\omega_p^h \in [0.0, 1.0]$ we observed smooth, low amplitude (50 units at hip-level) in-phase (no phase difference) oscillations. With a larger gain, the hip oscillations were limited to an amplitude corresponding to the rubber-band extension point and the ankle behavior was not smooth. We summarized these results in Figure 5.

With the second setting (τ_u = 0.06, τ_v = 0.65) a transversal analysis along the proprioceptive gain showed a variety of behaviors. For extreme values of ω_p^h (ω_p^h = 0 and $\omega_p^h > 6.0$), we did not observe any sustained oscillations, and amplitudes did not exceed the rubber-band extension point. Furthermore, manual pushes did not enable the system to stray around this "trivial" attractor. This result was predictable. With ω_p^h = 0.0, variations in the inertial angles resulting from the perturbation were not fed to the controller; and physical entrainment could not occur because the time-constants of the feedback loop and the control units were not compatible. On the other hand, with too high a gain ($\omega_p^h > 6.0$), the system was essentially driven by noise, thus leading to a pseudo-chaotic oscillatory behavior.

For intermediate values of ω_p^h, we observed multiple co-existing regimes. The value ω_p^h = 2.0 was particularly noticeable with three distinct regimes. From the resting position, a first quasi-stationary regime was obtained in which in-phase oscillations were sustained, albeit with very low amplitude (rub-
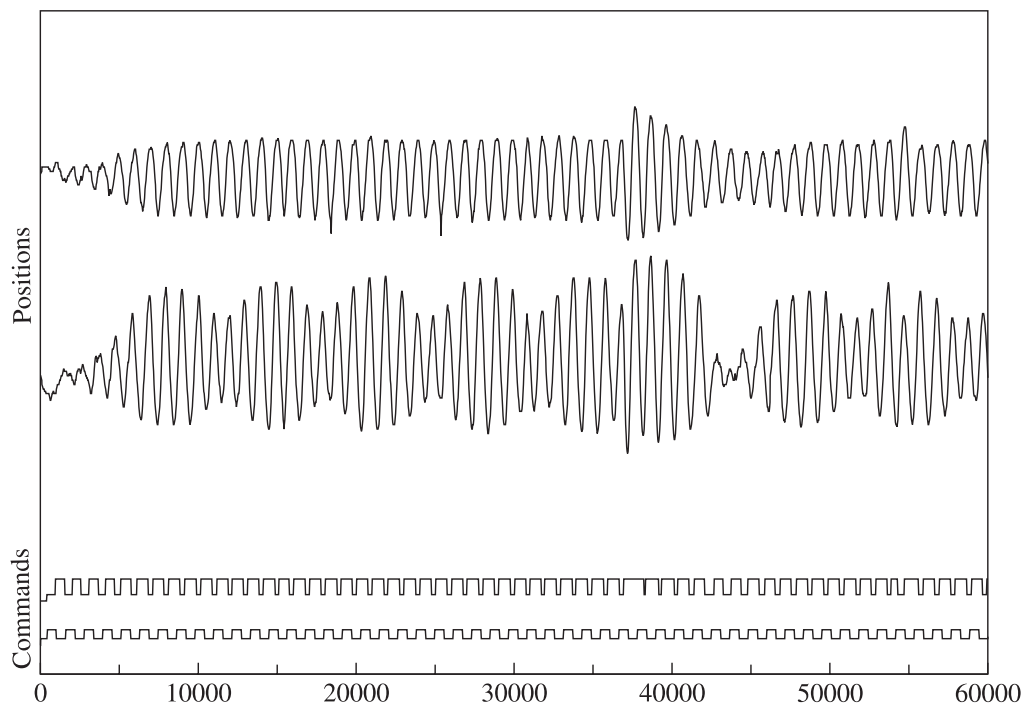
Figure 6   From top to bottom, time-series of hip and ankle positions, hip and knee motor commands with the following parameters: $\tau_u^h = 0.06$, $\tau_v^h = 0.65$, $\tau_u^k = 0.02$, $\tau_v^k = 0.8$ and $\omega_p^h = 2.0$. The horizontal axis denotes time (ms). The system was manually perturbed after about 37.5 s.

ber-band extension point) and with a continuous shift between the phases of the hip and ankle oscillations. After a manual push, a second stationary regime was reached in which larger hip oscillations occurred, but with an aperiodic hip–ankle phase plot. With yet another push, large in-phase smooth oscillations (amplitude 75 units) were obtained, similar to those obtained with $\omega_p^h = 0.5$. This regime was not robust against external perturbations and the system would subsequently settle in any of the three regimes. We found that this switching behavior was repeatable over various experiments.

From the point of view of the trade-off between stability and plasticity, i.e., stability to perturbation is desirable but not at the cost of learning plasticity, a systematic occurrence of this switching behavior across the entire control parameter space would be highly desirable as an intrinsic mechanism to strive around attractor states. Consequently, we carried out a set of experiments in which we fixed the proprioceptive gain to the critical value $\omega_p^h = 2.0$. The parameter space for the hip controller was explored with τ_u in the "usable" range [0.025,0.075]. The switching behavior could not be reproduced, however. Instead, all configurations produced a single stationary regime, robust to external

perturbations, with low-amplitude hip oscillations and generally non-periodic hip–ankle phase plots.

4.2.2 Instability of 2-Degrees-of-Freedom Exploratory Control   Using the hip parameter identified earlier ($\tau_u^h = 0.06$, $\tau_v^h = 0.65$), we realized a sparse exploration of the knee neural oscillator parameters with $\tau_u^k \in [0.02, 0.09]$ and $\tau_v^k \in [0.35, 0.8]$. Proprioception was fed to 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 movements.

This result was predictable. Because of its lack of proprioceptive feedback, the knee unit could not entrain with the hip oscillations. Meanwhile, the hip unit entrained to the oscillations resulting from the simultaneous motor commands of both hip and knee, thus inducing a continuous phase shift between hip and knee motor commands (see Figure 6). Because of the morphology of the system and the 3:2 ratio between hip and knee tonic excitations, hip oscillations were sustained, but both environmental perturbations and out-of-phase knee oscillations reduced the amplitude
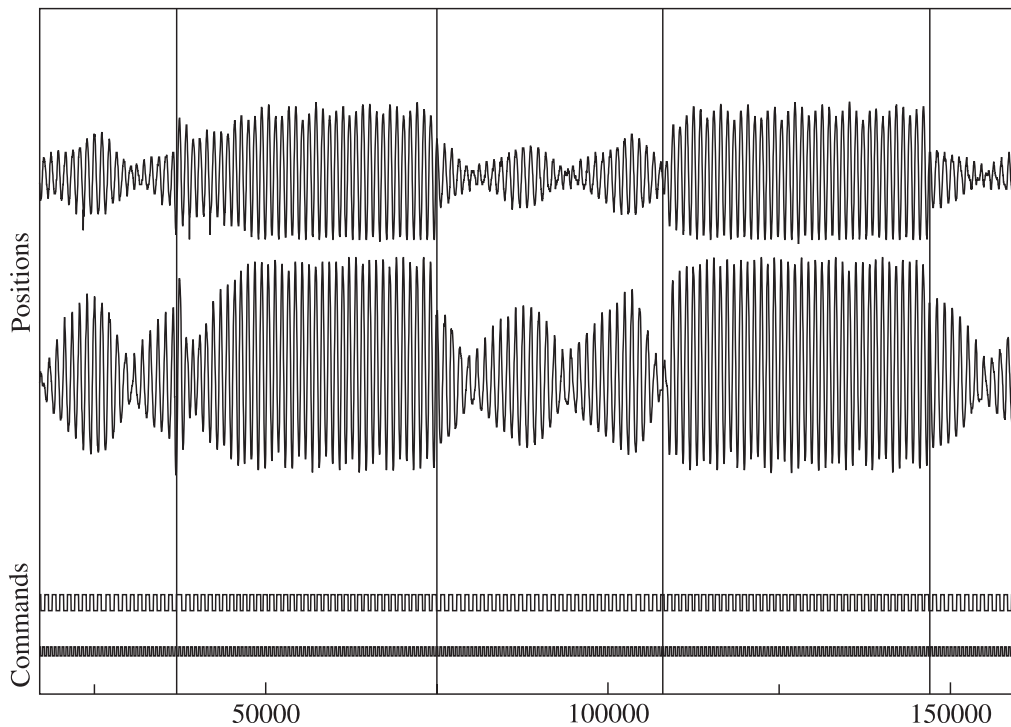
Figure 7 From top to bottom, time-series of hip and ankle positions, hip- and knee-motor commands with the following parameters: $\tau_u^h = 0.06$, $\tau_v^h = 0.65$, $\tau_u^k = 0.025$, $\tau_v^k = 0.35$ and $\omega_p^h = 0.25$. The horizontal axis denotes time (ms). The system was manually perturbed at time 37 s, 75 s, 108 s and 147 s (vertical lines).

of the oscillation to a nominal level. This interpretation was confirmed with experiments carried out with a small proprioceptive gain on the hip ($\omega_p^h = 0.25$). With a lower gain, the hip motor commands were not entrained as much to overall oscillations, and physical entrainment between knee and hip motor commands could occur because the phase shift was slower. Figure 7 illustrates the co-existence of two regimes when $\omega_p^h = 0.25$; and $\tau_u^k = 0.025$; $\tau_v^k = 0.35$. The first regime is qualitatively similar to the behavior observed in the previous instance (although in this case, the hip oscillations also exhibit a "wave-like" stationary regime). The second regime consists of large (55 units) in-phase oscillations.

To confirm further the hypothesis, we carried out a last batch of experiments in which the knee control unit was also fed with proprioceptive feedback. After fixing the knee unit parameters to $\tau_u^k = 0.06$, $\tau_v^k = 0.65$, we varied the knee proprioceptive feedback gain ω_p^h in the interval [0.0, 8.0]. We found oscillatory behaviors qualitatively similar to those obtained without proprioception to the knee, namely, low-amplitude hip oscillations, stationary regime robust to external perturbations. Higher gains led to a reduction of the

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

As in our initial study, the parameter ω_s, which determines the strength of the intersegmental coupling, played a crucial role. With too low a value, the coordination between hip and knee oscillators was very loose and we observed results qualitatively similar to the independent case. With a high value (here 1.0), a strong coupling occurred, and because the lower limb was mainly driven by the hip control unit, the system essentially became a *flexible 1-DOF* system (Lungarella & Berthouze, 2002a). To illustrate this point, we carried out the following experiments. The hip-unit parameters were initialized to ($\tau_u^h = 0.06$, $\tau_v^h = 0.65$), and the knee-control parameters (τ_u^k and τ_v^k) were set so that with an intersegmental coupling of $\omega_s = 0.0$ multiple oscillatory regimes could co-exist. We used the following values: $\tau_u^k = 0.035$, $\tau_v^k = 0.4$. The proprioceptive
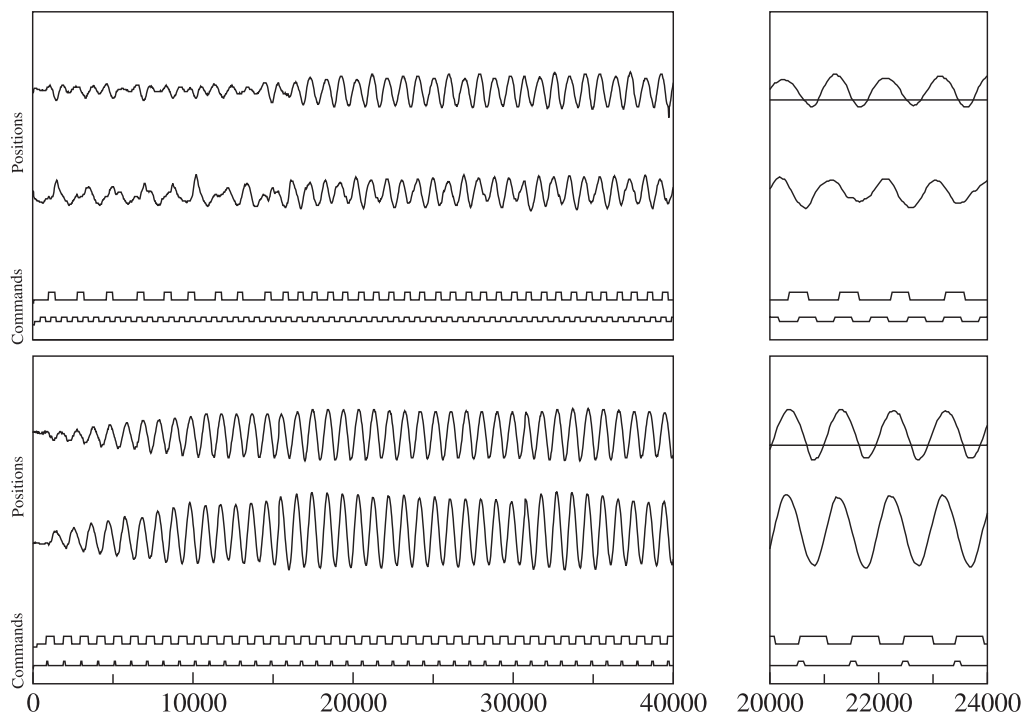
Figure 8 Co-existing regimes for $\omega_s = 0.0$ and $\tau_u^h = 0.06$, $\tau_v^h = 0.65$, $\tau_u^k = 0.035$, $\tau_v^k = 0.4$ (top). Unique in-phase oscillatory regime with $\omega_s = 1.0$ (bottom). In each graph, the time-series denote hip and ankle positions, hip and knee motor commands (from top to bottom). Right-hand windows are close-ups on the time-series. The horizontal axis denotes time (ms).

feedback gain to the hip was set to $\omega_p^h = 2.0$, i.e., its critical value as determined experimentally. With $\omega_s = 1.0$, the system stabilized into a stable regime in which hip and knee oscillated in phase (see motor commands in the close-ups of Figure 8). Interestingly, knee-kicking motion occurred only shortly before the robot reached the point after which the rubber band would have extended. From an intuitive point of view, this behavior could be optimal task performance.

With intermediate values, i.e., $\omega_s = [0.25, 0.75]$, the intersegmental coupling was not sufficient to overcome the difference in time-constants between the hip and the knee control units, and its effects were negligible. This outcome was in sharp contrast with our previous findings that intersegmental coupling (without proprioceptive feedback) could account for a reduction of transients and for the suppression of abrupt phase transitions. We had attributed that result to the effect of neural entrainment, whereby the outputs of the control units tend to smoothly converge towards a stable configuration (Lungarella & Berthouze, 2002b). In the case of physical constraints (the rubber band), however, a stable configuration cannot be systematically found.

4.2.3 Bootstrapped 2-Degrees-of-Freedom Exploratory Control As in the original study, we experimented with a controlled release of the second degree of freedom after the system had reached stationary regime in a 1-DOF configuration. We selected 1-DOF parameter configurations such as discussed earlier, but 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. Although this visual appraisal may appear to be an ad hoc solution, it actually helps validate our observations by introducing variance in the time after which the degree of freedom is released.

In contrast to the initial study in which all configurations led to a stable, in-phase stationary regime with large amplitude, the introduction of the second degree of freedom induced different behaviors that showed a relatively high sensitivity to the values of the knee-control parameters. We observed two typical situations. (1) The introduction of the second degree of freedom induced a phase shift that resulted in dampened oscillations, as shown in Figure 9 (left). This phenomenon was repeatable and robust to external perturbations. (2) When the 1-DOF regime was close
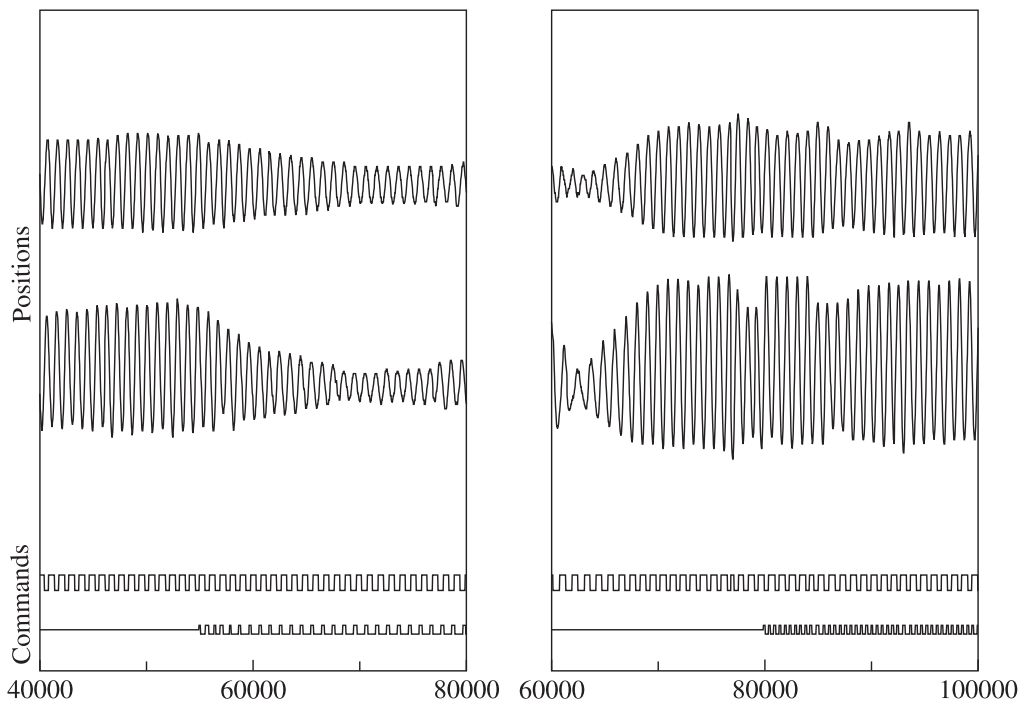
Figure 9   Results of the release of an additional degree of freedom after stabilization in a 1-degree-of-freedom configuration. Left: ($\tau_u^h = 0.045$, $\tau_v^h = 0.65$) and ($\tau_u^k = 0.025$, $\tau_v^k = 0.45$). Right: ($\tau_u^h = 0.06$, $\tau_v^h = 0.65$) and ($\tau_u^k = 0.025$, $\tau_v^k = 0.35$). From top to bottom, the time-series denote hip and ankle positions, hip and knee motor commands. The horizontal axis denotes time (ms).

to resonant control, the oscillatory behavior was left unchanged by the addition of a second degree of freedom, as shown in Figure 9 (right). Again, this is a natural result of the morphology of the system and the 3:2 ratio between hip and knee tonic excitations.

In further contrast with the initial study, we did not observe any instance where the introduction of the second degree of freedom led to better task performance. Instead, it often induced a collapse of the hip oscillations. We used these occurrences as a triggering signal for a new freezing–freeing phase of the peripheral degree of freedom. After freezing, the system always returned to an oscillatory behavior typical of its 1-DOF configuration. Subsequent releases led either to a new collapse of the hip oscillations, and thus, a new cycle of freezing–freeing, or to sustained oscillatory behavior (see Figure 10).

This result begs the question of whether freeing and freezing are just another form of perturbation. At this stage, we are not in a position to provide a definite theoretical reply. We are also not aware of any existing theoretical characterization of the effect of freezing–freeing on the motion patterns of human subjects engaged in tasks typically observed by developmental psychologists. We are not arguing against the fact that

a carefully designed perturbation, or a set of artificial constraints, could trigger the same type of motor changes as those induced by freezing and unfreezing. However, it does not appear plausible that infants rely on the likelihood of encountering such a particular perturbation to generate the appropriate chain of changes required for them to acquire their various skills. Indeed, developmental psychologists observe such sequence of change without having to introduce external biases. Thus, it seems reasonable to attribute these pathways of changes to an intrinsic mechanism like freezing and freeing (which could be seen as an intermediate stage en route to the self-organization of motor activities). Our experimental results show that unlike external perturbations such as a manual push, this mechanism can consistently and reliably lead the system to stray away from the sensorimotor area explored at the time of the "perturbation."

This could be interpreted in terms of the three stages of human motor-skill acquisition proposed by Goldfield (1995): (1) inability to control excessive degrees of freedom pushing infants outside the limits of their postural stability; (2) reduction of the number of degrees of freedom to simplify the control, either
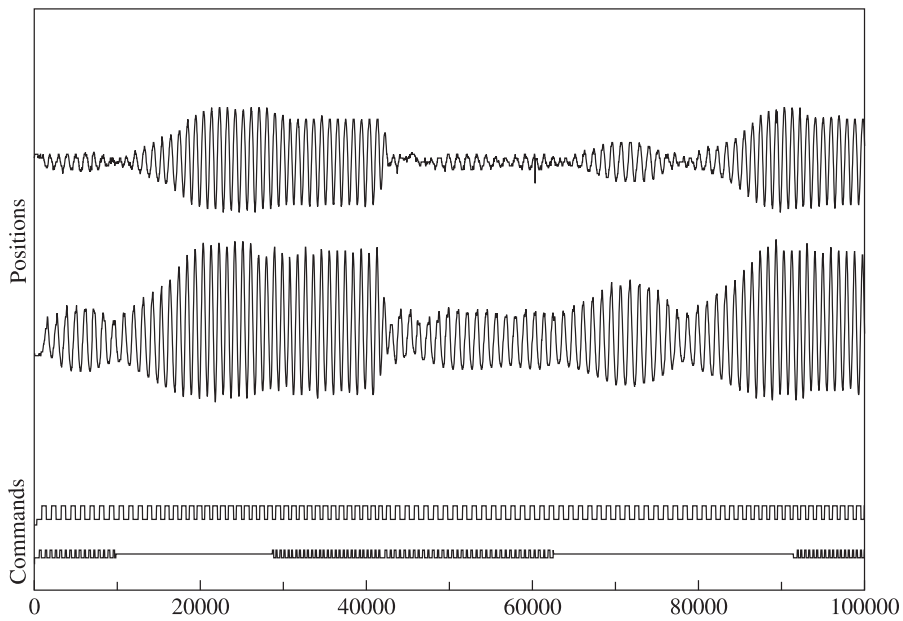
Figure 10 Oscillatory behavior obtained during alternate freezing and freeing phases. Neural parameters are unchanged and set to $\tau_u^h = 0.06$, $\tau_v^h = 0.65$, $\tau_u^k = 0.03$, $\tau_v^k = 0.325$, $\omega_p^h = 0.5$ and $\omega_s = 0.5$. From top to bottom, time-series denote hip and ankle positions, hip and knee motor commands. The horizontal axis denotes time (ms).
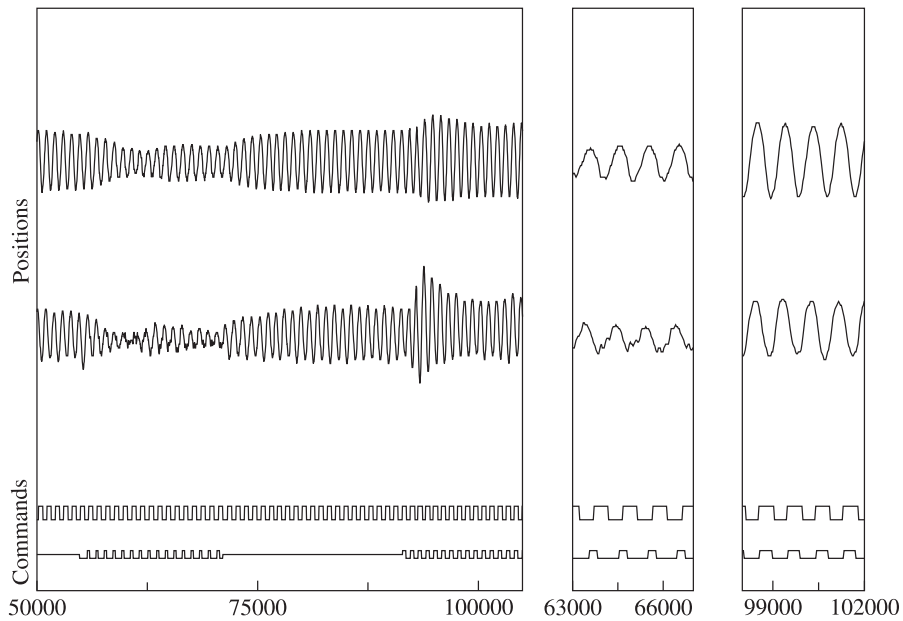

Figure 11 Effect of alternate freeing and freezing of the knee. Neural parameters are unchanged and set to $\tau_u^h = 0.035$, $\tau_v^h = 0.65$, $\tau_u^k = 0.055$, $\tau_v^k = 0.45$, $\omega_p^h = 0.5$ and $\omega_s = 0.5$. From top to bottom, time-series denote hip and ankle positions, hip- and knee-motor commands. Right-hand graphs are close-ups on the two different regimes. The horizontal axis denotes time (ms).

introducing synergies or by freezing degrees of freedom; (3) controlled release of the frozen degrees of freedom following recovery. Figure 11 shows empirical evidence for the effect of alternate freezing and freeing of the degrees of freedom. The close-ups on the right-hand side show that although the control parameters did not change, the kicking pattern of the knee did not change between subsequent releases.

5   Conclusions and Future Directions

In this study, we set out to assess whether an initial phase of freezing followed by a subsequent phase of freeing of degrees of freedom, such as proposed by Bernstein's model, would be sufficient to overcome the increase in task complexity induced by a strong nonlinear coupling between the pendulating robot and its environment. By comparing use of the full body and progressive exploration by using a developmental cycle of freezing and freeing of the degrees of freedom, we showed that a single stage of freezing–freeing was not sufficient to develop stable oscillatory behaviors. In contrast to our previous study (Lungarella & Berthouze, 2002b), alternate freezing and freeing was required. The interest of this result is twofold:

1. It confirms the recent observations by Newell & Vaillancourt (2001) that Bernstein's framework may be too narrow to account for coordination changes observed in motor learning (in adults as well as in children) (see also Haehl, Vardaxis & Ulrich, 2000; Ko, Challis, & Newell, 2003). According to Ko et al. (2003: p. 48), "there is growing evidence that there may not be, as suggested by Bernstein, a single pathway of change in the evolving patterns of coordination as a function of learning." Instead, depending on the task, there can be either an increase or a decrease in: (i) the number of involved mechanical degrees of freedom; and (ii) the dimension of the attractor dynamics of the motor output (number of dynamical degrees of freedom). Newell & van Emmerik (1989), for example, found no evidence of the freeing of the distal arm segments in the learning of signature writing, even though McDonald et al. (1989) found evidence of a release of the most distal wrist segment in learning a dart-throwing task with the non-dominant arm but only after several days of practice. Newell & Vaillancourt (2001) also reports that while open-chain linkages, such as arms and legs, are more prone to exhibit a proximal to distal direction to the recruiting of the biomechanical degrees of freedom, this pathway of change is only due to particular task constraints and may not be a general learning strategy. This interpretation is supported by the study of Haehl et al. (2000) on infants learning to cruise (walking with support). This study showed that infants displayed an initial poorly controlled exploratory phase—*wobbling* phase—characterized by a large number of movement reversals (i.e., dynamical degrees of freedom).

2. It provides empirical evidence suggesting that perturbations that push the system outside the limits of its postural stability, or which increase the complexity of the task, may be the triggering mechanism for alternate freezing and freeing of degrees of freedom. As with Newell & Vaillancourt (2001), this study doesn't allow us to further speculate on: (i) the factors responsible for the multiple pathways of change observed in the learning of motor coordination (besides task-dependence, and confluence of constraints in action); and (ii) how those factors combine with the neural dynamics to implement those changes. However, we believe that it provides opportunities to investigate further the issue of increased task complexity and task constraints. Recently, we have started investigating a robot-*bouncing* task by taking inspiration from a longitudinal study by Goldfield, Kay, & Warren (1993) on infants' bouncing in a Jolly Jumper, i.e., a harness hung from the ceiling by springs or rubber bands. Some preliminary results that substantiate the claims made in the present paper have been published (Lungarella & Berthouze, 2004).

This study points at two challenges to be addressed in the future: the first one relates to the proper characterization or description of the multiple pathways of change observed during the learning of motor patterns in a given task. Taking a biomechanical stance, we could quantify the motor activity in terms of *biomechanical* degrees of freedom, i.e., the change over time of the number of joints or muscles responsible for the particular coordination strategy employed to accomplish the task. A dynamical systems perspective, on the other hand, would refer to the *dynamical* or *active degrees of freedom* that correspond to the geometric layout of the attractor dynamics. In the case of simple patterns of coordination, such as the one in our initial study, it may be justified to attribute to a single variable, e.g., the relative phase between limbs, the role of *order parameter*, or *collective variable* (Kelso, 1995). Even then, however, the motion of a single joint can yield a dimension greater than one. As for whole body action, "we have little understanding of the number or the nature of dimensions that capture the collective organization of the system" (Newell & Vaillancourt,

2001). Thus the matching of those two dimensions (biomechanical and dynamical) is a major challenge.

The second point is closely related to the first and concerns the tight interaction between neural dynamics and bodily activity. In our two studies, we intentionally focused on the role of physical (morphological) changes for a fixed control parameter setting (i.e., a given neural organization). Although this step was useful—it helped us demonstrate experimentally that such changes represent an adaptive mechanism in their own right—it lacked biological plausibility, causing the relatively poor performance obtained in the face of strong perturbations. In reality, neural dynamics entrains to physical dynamics (as shown by control synergy, for example) and control re-organization occurs as a result of learning. In this respect, the choice of Matsuoka oscillators is arguable. This type of oscillator has been shown to have poor characteristics when feedback-induced delay increases above a certain value (see for instance Taga, 1994). We hypothesize that, in this study, the nonlinear coupling may have introduced a significant feedback delay, which in turn resulted in the failure to entrain. Asymptotically stable limit-cycle oscillators with physiologically plausible characteristics, e.g., the Bonhoeffer–Van der Pol model (Fitzhugh, 1961), are possible alternatives to Matsuoka's model, because they exhibit *flexible phase-locking*, i.e., they show greater flexibility in changing their relative phase to respond to incoming entraining actions, even in the presence of strong delays (Ohgane, Ei, Kazutoshi, & Ohtsuki, 2004).

Finally, we would like to comment briefly on an important issue raised by a reviewer, namely that of the difference between exploration and learning. Is this case study about learning or is it simply about the exploration of the sensorimotor space during pendulation. In what way does it relate to development? In our framework, exploration is a key component of task acquisition. Exploration produces the diversity of sensorimotor trajectories (instances of task executions) that higher brain systems can subsequently select, and exploit to realize learning, for example, in the form of consolidation of a parameter in motor memory, or to train forward models (e.g., Wolpert, Doya, & Kawato, 2003). With a few exceptions, most motor tasks require practice before optimal performance is achieved, and in young infants—at a stage when they have not acquired many primitive motor behaviors on top of which to build more complex skills—the role of exploration is critical. The

use of a value-based learning algorithm, such as the one discussed in the Appendix, implements a first step towards learning, as exploration is driven by value, i.e., task performance. In the original study, we showed how such value-driven exploration led to a quick convergence to a stable motor behavior. Thus, exploration should be seen as an adaptive (plastic) mechanism in its own right, although it acts on a different ontogenetic timescale than that of learning or development.

Note

1   During task-dependent movements, the joints are not controlled individually, but are coupled in such a way that they change relative to each other. This coupling is called a joint synergy.

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# Appendix

Value-Based Exploration Algorithm

In line with our interpretation of swinging as a *circular reaction*, we devised a simple value system to guide the exploration of the parameter space associated with the control structure of the robot. In this section, we reproduce the essence of the algorithm. For additional details, the reader should refer to Lungarella & Berthouze (2002b). The value system investigated in that particular study was a function of the maximum amplitude of the oscillation, which was evaluated within a given time window through markers placed on the robot's body. The value at time t was given by

$$V_t = max\{V_{t-1}(1 - \varepsilon), |A_t|\} \tag{5}$$

where $|A_t|$ denotes the absolute value of the instantaneous amplitude of the oscillation. The term $(1 - \varepsilon)$ with $0 < \varepsilon << 1$, realized an exponential decay of the value signal when the oscillations were smaller than the previously achieved maximum amplitude. With an appropriate selection of ε, the decay was not rapid enough for the value to decrease within a single period of a stable oscillation (whose frequency was in the range of the control frequencies considered in the study). We adopted the following *exploration principle*: when a parameter setting yielded a good performance (i.e., a high value V_t), the change of parameters (step size of the exploration) slowed, and hence nearby sets of parameters were exploited. Conversely, a rapid and large change in parameters was triggered when the settings led to low-amplitude oscillations. This is classically referred to as *exploration–exploitation dilemma*: on the one hand, the system should explore its parameter space, on the other, it should exploit good parameter configurations that the exploration has already uncovered. We also realized a simple form of habituation, that is, a decrease in strength of the output of the value systems over time. We implemented it as an exponential decay of the value v when the system remained in a stationary regime of sustained oscillation for a certain amount of time. The decay of value led to an increase of the step size of the exploration and new areas of the parameter space were explored.

About the Authors
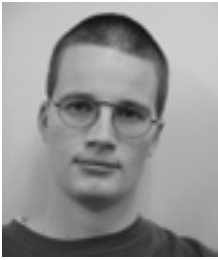
Luc Berthouze received his Ph.D. in Computer Vision from the University of Evry (France) in 1996. He joined the Electrotechnical Laboratory (ETL) of Japan in 1995 as an invited researcher, and in 1996 as a permanent researcher. Since 2001, he has been a research scientist at the Neuroscience Research Institute of AIST, Japan. With research interests in developmental psychology, cognitive science, neuroscience, and dynamical systems, he focuses on motor learning and its role in the emergence of embodied cognition.

Max Lungarella is a Ph.D. candidate at the Artifical Intelligence Laboratory of the University of Zurich, Switzerland. Currently, he is an invited researcher at the Neuroscience Research Institute of AIST, Japan. He has been involved in various projects related to embodied artificial intelligence. His research interests include, but are not limited to, embodied artificial intelligence, developmental robotics, and electronics for perception and action. *Address:* Neuroscience Research Institute (AIST), Tsukuba AIST Central 2, Umezono 1-1-1, Tsukuba 305-8568, Japan. E-mail: Max.Lungarella@aist.go.jp