A Synthesis of Bipedal Locomotion in Human and Robots

Christine Azevedo Coste, Bernard Amblard, Bernard Espiau, Christine Assaiante

INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

A Synthesis of Bipedal Locomotion in Human and Robots

Christine Azevedo — Bernard Amblard — Bernard Espiau — Christine Assaiante

N° 5450

December 2004

Thème BIO

Rapport de recherche

ISSN 0249-6399 ISRN INRIA/RR--5450--FR+ENG

A Synthesis of Bipedal Locomotion in Human and Robots

Christine Azevedo* , Bernard Amblard†, Bernard Espiau‡ , Christine Assaiante†

Thème BIO — Systèmes biologiques
Projet DEMAR

Rapport de recherche n° 5450 — December 2004 — 55 pages

Abstract: This report is the result of a joint reflection carried out by researchers from automatic control and neuroscience fields, both trying to answer a same question: what are the functional basis of bipedal locomotion and how to control them?
The originality of this work is to put in parallel two synthesis of how the problem of biped displacements is solved in robotics in one hand and in nature in the other hand. We believe that the key elements explaining the performances in adaptability and reactivity of human could help roboticians to find some issues for the design of automatic control schemes. Similarly, the theoretical framework of biped robotics could help neuroscientists to formulate concepts and models.

Key-words: postural control, biped robots, equilibrium, walking

* INRIA Sophia Antipolis - LIRMM, 161 rue Ada, 34092 Montpellier cedex 5, FRANCE
† DPA P3M CNRS, 31 chemin Joseph Aiguier, 13402 Marseille Cedex 20, FRANCE
‡ INRIA Rhône-Alpes, Zirst 655 avenue de l'Europe Montbonnot, 38334 Saint Ismier Cedex, FRANCE

Unité de recherche INRIA Sophia Antipolis
2004, route des Lucioles, BP 93, 06902 Sophia Antipolis Cedex (France)
Téléphone : +33 4 92 38 77 77 —Télécopie : +33 4 92 38 77 65

Synthèse de la locomotion bipède chez l'homme et les robots

Résumé : Ce rapport est le résultat d'une réflexion commune qui a été menée par des chercheurs en automatique et en neurosciences cherchant à répondre à une même question : quelles sont les bases fonctionnelles de la locomotion bipède et comment les contrôler ? L'originalité de ce travail est de mettre en parallèle deux synthèses sur la façon dont le problème du déplacement bipède est résolu en robotique d'une part et dans la nature d'autre part. Nous pensons que les éléments clés conduisant à des performances d'adaptabilité et de réactivité chez l'humain pourraient aider les roboticiens à trouver des voies de solution pour la conception de schémas de commande. De la même manière, le cadre théorique de la robotique bipède pourrait aider les neuroscientistes à formuler des concepts et modèles.

Mots-clés : contrôle postural, robots bipèdes, équilibre, marche

Contents

1 Introduction **4**

2 Basic concepts in bipedal robotics **5**
- 2.1 Biped systems . . . 5
- 2.2 Dynamics . . . 7
  - 2.2.1 Continuous dynamics . . . 7
  - 2.2.2 Impacts . . . 8
- 2.3 Stability and equilibrium . . . 8
  - 2.3.1 Static equilibrium and posture . . . 9
  - 2.3.2 Dynamic equilibrium and stability . . . 11
- 2.4 Synthesis of artificial biped locomotion . . . 12
  - 2.4.1 Use of predefined trajectories . . . 13
  - 2.4.2 On-line synthesis of the motion . . . 18

3 How does human walk: a functional description **22**
- 3.1 Principles of the postural control . . . 23
  - 3.1.1 Postural orientation and postural stabilization . . . 23
  - 3.1.2 Postural and locomotor equilibrium . . . 24
  - 3.1.3 Spatial reference frames and segmental stabilization strategies . . . 25
  - 3.1.4 The trunk, leader segment of human locomotion . . . 26
  - 3.1.5 The limbs, effectors of locomotion . . . 27
  - 3.1.6 Role of the head . . . 28
- 3.2 Hierarchical control architecture . . . 28
  - 3.2.1 Hierarchical organization of the central nervous system . . . 29
  - 3.2.2 Movement control . . . 30
  - 3.2.3 Postural control . . . 31
- 3.3 Optimizing the postural tasks . . . 34
  - 3.3.1 Reducing of the number of variables to control . . . 34
  - 3.3.2 Building up classified repertories . . . 34
  - 3.3.3 Postural body scheme . . . 35
  - 3.3.4 Minimization of the energy consumption . . . 36
  - 3.3.5 Minimizing the consequences of signal-dependent noise . . . 37
- 3.4 Locomotor development and training : why and how? . . . 37

4 Conclusion **39**

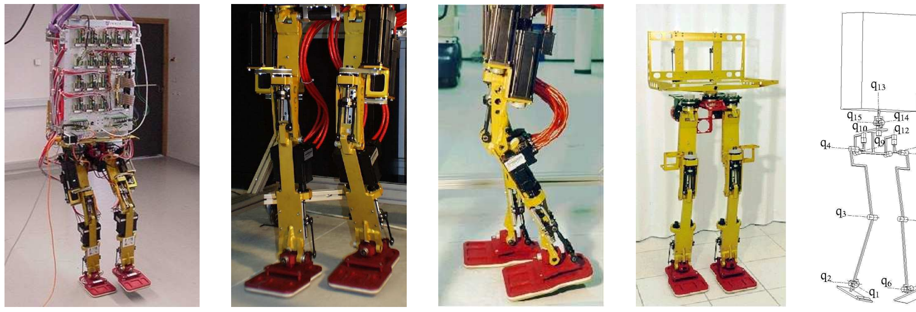


Figure 1: BIP (INRIA and LMS) skeleton [75]

1 Introduction

This report addresses the problem of controlling 2-legged systems that can be natural or artificial, therefore concerning both neuroscientists and roboticians who are working on a similar question with different approaches: analyzing control modes of bipedal standing and walking.

Researches on the control mechanisms of human displacements are still going on and many hypotheses remain a matter of great controversy between neuroscientists. On the other hand, researchers in the field of robotics are building bipedal machines, trying to achieve the great feat managed by slow evolution of human specie. Neuroscience and robotics, respectively concerned with living beings or with artificial structures, are both oriented to the understanding of bipedal locomotion. Nevertheless poor intersection exist between these two fields of investigation.

This paper places in parallel the results elicited in robotics and in neuroscience concerning the control of equilibrium and walking. We will also try to define borders for the analogy between artificial and natural systems. We believe that a better understanding of human motor control can help to develop new issues to explore in order to enhance robot controller capacities. We also believe that the theoretical framework and tools concerning robot walking can find out an application in the analysis of human walking.

The paper is divided into two parts: first section is an overview of the basics concepts existing in bipedal robotics and the second section is a functional description of how human stands and walks.

2 Basic concepts in bipedal robotics

2.1 Biped systems

Biped robots like other legged (or walking) machines are a particular class of mobile systems. Legged robots raise design and control problems which differ from other mobile machines, like wheeled or tracked ones. The applications they are aimed at are also particular. Legs are well adapted to move in cluttered up environments where they can overcome obstacles. Legged locomotion allows a minimal and selective invasion of the ground by placing the feet in suitable positions in order to preserve the environment (cultivated land, field...). This should give rise to outdoor applications as various as agriculture and field robotics, mine clearance, exploration, forest exploitation. When considering structured environments, legged systems, and particularly biped ones, look well-suited for climbing stairs, walking through corridors or moving and acting in rooms designed for human occupancy.

Now, a frequently asked question is: why building biped robots? In fact, different applications can be envisioned when developing a biped robot and then guide the design of the prototypes. Their anthropomorphic size is well adapted to **service and assistance** tasks to help human in his private and/or working activities [29]. Due to their likeable and reassuring aspect, these robots have also application in **entertainment**, toy industry and advertising [103]. Japanese companies like Honda Motor Co (ASIMO), Sony (QRIO) [14, 175] or KAWADA (HRP2) have taken a large technological advance in the goal of creating machines capable of entering home and assisting people. They emphasize in so-called "human friendly design" in order to gain acceptance by the public. In that sense legs are not only a technology of motion but also a way to charm human users [125]. Some research teams are working on biped robot to gain hints in **biomechanics and rehabilitation** techniques such as orthoses, prostheses and exoskeleton design and control or functional electrostimulation (FES) [74] but also in understanding mechanisms of motor control [198]. This leads to the construction of anthropomorphic systems allowing analogies and comparisons with human, like BIP (INRIA and LMS, France), WABIAN (Waseda University, Japan), Johnnie (TUM, Germany) [28, 203, 115] and others. Nevertheless, anthropomorphism is not the only issue: some bipeds are also designed on different models: dinosaur like [197], bird-like [181, 192]...

Biped robot skeleton is classically made of aluminium [115], but not always: polymers can also be used, end even wood [190]. The segments are interconnected by means of joints which are generally active. The complexity of the prototypes can vary from very low to high number of degrees of freedom [144, 175]. Generally the systems are composed of two legs, a trunk, two arms and one head. Legs are classically composed of six actuated joints (fig.1): three for the hip, one for the knee and two for the ankle. Except in a few recent prototypes, the torso is usually one single rigid part. Few robots have joints placed between torso and legs for them to be independent [28, 203, 115]. The majority of robots are operated through electric motors which are easy to control. The major problem is to convert the rotational

Figure 2: Some joints of the BIP robot (INRIA and LMS)

output to a linear one and this is achieved by means of dedicated mechanical transmitters (fig.2). There also exist systems using substitutes for the human actuators, like artificial muscles which are contractile devices mimicking natural muscles in terms of strength to weight ratio and response speed, inherently compliant, but with significant nonlinearities in their behavior [190, 87].

The main characteristic of walking robots is that they do not have a fixed base. In bipedal walking, **phases of single support and double support alternate**, corresponding to opened and closed configurations of the kinematic chain composed by the robot skeleton. Therefore the number of degrees of freedom varies from one phase to another. Since the number of active joints remains constant, a same system can be underactuated or overactuated depending on the ground contacts. In running, there exists phases where no point at all of the robot is in contact with the ground.

Here, we may point out a major difference between robots and humans: humans can walk *and* run. Today, robots are designed and optimized for either walking *or* running, but few artificial system are able to perform both tasks, except a few specific prototypes [14, 175] or in very special conditions, like in [176] where the robot is constrained in the sagittal plane.

Sensors are of high importance for the control of robots. They should give proprioceptive information to the controller: encoders to measure joint angles, gyrometers, accelerometers or inclinometers to measure the absolute position of the system in the space. Exteroceptive sensors are also required to allow the robot to evolute in an unknown environment: vision cameras, acoustic, infrared sensors. Force sensors should provide a fairly good indication of, basically, the occurrence of a contact with the ground, and, more, of the value of the associated wrench.

The ultimate robot should be self energically autonomous. It is far to be the case, most of the systems having energy supplied from wires. Some of them carry batteries, like the Japanese humanoid HRP-2 from KAWADA, able to walk more than one hour. HONDA's ASIMO exhibits comparable results The progress is important when recalling that the HONDA previous prototype P2 needed 20 kg of batteries to walk for 15 minutes [103].

2.2 Dynamics

When walking, a biped interacts with the ground, therefore **locomotion results in a sequence of continuous and discontinuous phases**, where the impacts are discrete events triggering the displacement [106]. Therefore biped machines are hybrid nonlinear systems.

2.2.1 Continuous dynamics

Under the assumption that the robot structure is rigid, continuous dynamics can be expressed under the Lagrangian form:

$$M(q)\ddot{q} + N(q,\dot{q})\dot{q} + G(q) = \Gamma + \Gamma_{ext} \tag{1}$$

where: $q \in \mathbb{R}^n$ stands for the parametrization vector of the whole configuration space of the robot considered as free in the 3D space[1]; $\Gamma = [0,\tau]^T \in \mathbb{R}^n$ is the generalized effort vector including joint actuation torque (generally bounded), $\tau \in \mathbb{R}^m$; M is the inertia matrix; N is the centrifugal, gyroscopic and Coriolis effects; G is the generalized gravity force vector. Note that the set $(q,\dot{q})$ constitutes the **state** of the robot, in the sense of the theory of dynamic systems. Γ_{ext} are the torques generated by external forces like ground contacts, a thrust... They can be expressed as:

$$\Gamma_{ext} = C(q)^T \lambda(q,\dot{q})$$

$C(q)$ is the Jacobian matrix of the points of the robot on which the external forces are applied and $\lambda(q,\dot{q})$ corresponds to the amplitudes of these forces.
If $\phi(q)$ are the coordinates of the points submitted to external efforts, then:

$$C(q) = \frac{\partial \phi(q)^T}{\partial q}$$

Biped dynamics is characterized by the existence of variable constraints resulting from the interaction with the ground. Ground efforts correspond to a set of forces applied on each point of the robot in contact with the ground.

$$\Gamma_{ext} = C_n(q)^T \lambda_n(q,\dot{q}) + C_t(q)^T \lambda_t(q,\dot{q})$$

Subscripts $_n$ and $_t$ stand for normal and tangential to the ground components respectively. Lagrange multipliers λ_n and λ_t express the amplitudes of the effort components.
A common way of modeling those specific external forces is to consider the robot as a chain of rigid bodies in tree form in rigid interaction with the ground through unilateral links and

[1] In the whole document, $\dot{x}$ and $\ddot{x}$ stand respectively for the first and second order time derivatives of the variable x.

friction. The points of the robot in contact with the ground verify a closure equation of the form:

$$\phi(q) = \begin{pmatrix} \phi_n(q) \\ \phi_t(q) \end{pmatrix} = 0 \tag{2}$$

The assumption of non penetration results in unilateral constraints which imply semi-positive normal forces and accelerations of the contact points which are related by a complementarity condition: [169, 212]:

$$\lambda_n^T(q,\dot{q})\ddot{\phi}_n(q) = 0,\ \ \lambda_n(q,\dot{q}) \geq 0,\ \ \ddot{\phi}_n(q) \geq 0$$

Excluding the case where the system is slipping, tangential constraints can be written as:

$$\ddot{\phi}_t(q) = 0$$

Finally, since the existence of friction induces bounds on the tangential forces, a non-slipping condition is satisfied as long as:

$$\|\lambda_t\| \leq \mu_0 \lambda_n$$

where: μ_0 is the friction coefficient depending on the materials in contact.

2.2.2 Impacts

When one point of the system enters in contact with the ground, an impact occurs inducing a velocity deviation. The velocity of the system before impact: $\dot{q}^-$ takes a new value: $\dot{q}^+$

$$M(q)(\dot{q}^+ - \dot{q}^-) = C_n(q)^T \Lambda_n(q,\dot{q}) + C_t(q)^T \Lambda_t(q,\dot{q}) \tag{3}$$

where: $\Lambda(q,\dot{q}) = [\Lambda_n(q,\dot{q}), \Lambda_t(q,\dot{q})]^T$ is the vector of the amplitudes of the impulsion forces. Under the assumption that contact points do no slip neither take off after impact we can write:

$$\dot{\phi}_n(q) = C_n(q)\dot{q}^+ = 0 \ and\ \dot{\phi}_t(q) = C_t(q)\dot{q}^+ = 0$$

Note: The dynamics (continuous and impacts) can also be expressed in terms of an equivalent Quadratic Programming problem [212].

2.3 Stability and equilibrium

Stability and equilibrium are key concepts in biped systems, since they are closely related to the risk of falling. The stability concept is well understood and nicely formalized for many classes of dynamics systems, even nonlinear, as explained in any textbook of automatic control. However, these approaches cannot be applied in a straightforward way to bipeds, mainly because of the particular nature of contact constraints. Furthermore, the steady state walking process in itself can be seen as "stable" even though some usual stability criteria are not fulfilled. It is therefore necessary to go beyond an only intuitive understanding of these concepts and to try to exhibit more formal issues. In that way we will split the presentation in two parts: statics and dynamics, which will both largely rely on P.B. Wieber's work [212, 210].

2.3.1 Static equilibrium and posture

Let us come back to the dynamics presented in section 2.2.1. The parametrization q, which represents the robot configuration is in fact the concatenation of two elements, q_1 and q_2. The vector q_1 is the parametrization of the position and the orientation of a given robot body in the 6-dimension displacement manifold, it is expressed with respect to a fixed galilean frame, for example ground-related; q_2 represents the **internal configuration** of the biped, which can be seen as its **posture**. Usually, it is the set of the joint coordinates, for example in the case where the robot is a tree-form open kinematic chain. When local closed chains (i.e. which are expressed by closure algebraic equations representing the associated bilateral homonomous constraints) exist, q_2 is the set of the mobilities of the system, the way of parameterizing them being then different from one case to another.
In a way analogous to the splitting of the configuration, it can be shown that the dynamics (1) can be rewritten as:

$$\begin{cases} M_1(q)\ddot{q} + N_1(q,\dot{q})\dot{q} = \ 0 \ + C_1(q)^T\lambda - G_1(q) \\ M_2(q)\ddot{q} + N_2(q,\dot{q})\dot{q} = \tau + C_2(q)^T\lambda - G_2(q) \end{cases} \tag{4}$$

where we recall that τ is the set of actuator torques, all joints being assumed here to be actuated.
It can be shown that the left-hand side of the first line of eq.(4) is equivalent to the dynamic wrench of the system, while the right-hand one is equivalent to the wrench of contact and gravity forces. This equation is of the Newton-Euler form, the Newton part being to be expressed easily in terms on the acceleration of the Center of Mass (CoM) of the robot. This shows a fundamental issue: **the global displacement and orientation of the robot can only be realized owing to contact forces**. Furthermore, this motion is necessarily associated with a change of the posture. All these facts are obvious in zero-G condition.

Let us now explain the concept of **static equilibrium**. A configuration q_{eq} corresponds to a static equilibrium of the system if: $\dot{q_{eq}} = \ddot{q_{eq}} = 0$; i.e. the left-hand sides of (4) vanish. If such a configuration exists, it is such that, at this point, the set of contact forces and joint actuator torques compensate for the gravity effect. Of course, such a set doesn't always exist. When the contact points are all in a same horizontal plane, only normal contact forces have to be considered. Coming then back to the static wrench allows easily to show that the static equilibrium condition reduces to the classical one: the projection of the robot's center of mass belongs to the convex hull of contact points: $x_{CoM} \in \mathcal{D}$. In other cases, tangential forces have to be taken into account.

Let us now introduce a time variation of q_{eq}. Then the previous equilibrium condition becomes:

$$x_{CoM}(t) \in \mathcal{D}(t) \quad \forall t \in [0, T] \tag{5}$$

where T is the considered temporal horizon. Among these time-varying trajectories, some characterize the so-called **static walking**, a first definition of which is now possible:
A static walk is a walk (i.e. a continuous sequence of configurations ensuring the forward progression and maintaining the erected position of the system simultaneously) such that at each instant the static equilibrium condition (5) is satisfied .
Obviously, the trajectory of $x_{CoM}(t)$ should be continuous[2]. This requires that $\int_0^T \mathcal{D}(t)dt$ is connex, which implies that, necessarily, a static walk includes double support phases.

A last point to be addressed in this section devoted to static equilibrium is the one of **postural control**. This expression is largely used in biomechanics and neuroscience domains, and deserves here to be formalized. Recalling that **posture** is no more than the internal configuration, it is clear that any kind of control is "postural" in some sense, since the associated subset of parameters, q_2, is involved in all cases! However, in order to be coherent with the common, although sometimes intuitive, understanding of this concept, we may try to give a specific definition of postural control in robotics.
Let us consider the case where, despite the fact that the equilibrium configuration q_{eq} is time-varying, we have $\mathcal{D}(t) = \mathcal{D}(0) \quad \forall t \in [0, T]$. The set of contact points is therefore fixed. Assuming that all forecoming motions will not affect the contact forces in such a way that this set be modified, the posture may therefore evolve in the time while ensuring that eq.(5) is satisfied with $\mathcal{D}$ constant. However, for this kind of behavior to be allowed, it is necessary to be sure that the submanifold in which q can live is not zero dimensional. This point is linked to the concept of **task redundancy** [37]. Briefly, the basis is to define some "priority" tasks under the form of algebraic equations, which have to be achieved whatever the posture. Clearly, a first one is needed to satisfy constraint eq.(5), for example: $x_{CoM}(q(t)) - x_{CoM}(q(0)) = 0$, which is 2-dimensional. Other ones depend on the application: keeping constant the height of the CoM, maintaining the head or/and the arms motionless, etc... In any case, these other tasks should be all gathered under the form $f(q(t)) = 0$, assumed to be m-dimensional.
Finally, a postural modification, under the constraint of achieving the priority tasks, is intuitively possible if $2 + m < n - 6$. This desired modification, which may be for example a trajectory specified in an appropriate space, has the status of a secondary task. If the dimension of the desired modification is exactly $n - 6 - (m + 2)$, and if all the tasks are compatible and independent, they can be theoretically perfectly achieved. If the dimension of the secondary task is greater, then it can be expressed as the gradient of a function to be minimized, which is projected on the priority task including constraint eq.(5) [155]. In that case, the secondary tasks can only be completed approximately. The so-called postural control can therefore be finally defined as a control scheme which is aimed at ensuring the physical realization of all these tasks.

[2] but non necessarily twice-differentiable everywhere, because of impacts.

2.3.2 Dynamic equilibrium and stability

The concept of **dynamical equilibrium** is a little more difficult to approach formally. We can for example say that a system represented by a nonlinear differential equation is in dynamical equilibrium if, starting from given initial conditions, it stays on a closed curve in the phase space, i.e. a close orbit. We will come back later to this point. In the case of biped robot, *the dynamical equilibrium can be intuitively linked to the idea of a possible movement.* In fact, the system can achieve a desired movement if and only if the total wrench of gravity and contact forces is equal to the dynamic wrench of the robot.
In the case where all contact points are in the same plane, it can be shown that there exists a point in this plane around which the horizontal rotation momentum of gravity and dynamic forces vanishes. This point is known as **Zero Moment Point** (ZMP-[202]), but it is also no more than the **Center of Pressure** (CoP). When accelerations and velocities are equal to zero, this point is simply the projection of the Center of Mass (CoM) evoked in the previous section.
However, this point can't be used to characterize the dynamical equilibrium as the possibility of achieving a motion which maintains the CoP inside the convex hull of contact points, as soon as these contact points are *not* in the same horizontal plane. Specific derivations are then needed. Moreover, tangential (sliding) forces are not taken into account in a ZMP-based approach. A right and generic way of stating the **walking stability** is expressed in [212] under the form: a necessary condition for a walking system to realize a motion specified by a trajectory $q(t)$ on a given time interval is that there exists contact forces $\lambda(t)$ such that

$$\begin{cases} M_1(q)\ddot{q} + N_1(q,\dot{q})\dot{q} + G_1(q) = C_1(q)^T\lambda \\ \mathbf{A}(\lambda) \geq 0 \end{cases} \tag{6}$$

where the vector inequality $\mathbf{A}(\lambda) \geq 0$ denotes all constraints on normal (unilaterality) and tangential (Coulomb friction) forces.
Finally, the motion can definitively be achieved if the actuation forces are able to meet the dynamical requirements of the second equation of eq.(4).

Let us now come to the idea of **stability**. Equilibrium and stability are obviously independent concepts, since an equilibrium can be stable (a simple pendulum submitted to viscous friction and gravity at rest) as well as unstable (the same pendulum, but inverted). Roughly, an equilibrium can be said as stable[3] if, when we constrain the system to leave this equilibrium, it comes back to the equilibrium if we relax the constraint. For static equilibrium, that means that a (small) disturbance is absorbed by the biped, which will later move in such a way that the projection of the CoM comes back to its previous position. This can be done for a small part by some internal viscoelasticities, but mainly using an adequate control scheme, for example a classical PD joint control. Nevertheless, these issues are not sufficient to characterize the stability of a biped: let us consider again the robot standing at a stationary position, i.e. having his joint variables regulated at a given value satisfying

[3] asymptotically stable in fact...

constraint (5). As said previously, if we slightly disturb this equilibrium, the robot can be driven back to its goal position, but if the disturbance is large enough, this is not sufficient and the robot will avoid to fall only by stepping forward, i.e., by changing his reference trajectory (leading to a new contact point configuration).
This illustrates the fact that the stability of walking systems has to be understood in a sense different from classical dynamical systems, the main issue being to avoid falling (i.e. reaching a position where other points that the feet are in contact with the ground). Extending the idea of redundancy in postural control, we can say that **the priority task for a robot is to maintain its equilibrium in the sense of avoiding to fall**, all the other objectives (desired velocity, direction of motion, type of the gait, object grasping, etc...) being to be addressed only when the first one is ensured. The difficulty now is to relate this intuitive notion to adequate formal aspects. Only a few attempts to derive a general approach of this question can be found in the literature. The deeper existing analysis seems to be the Wieber's one [210], to which we refer the reader for all technical aspects. Let us just give a glimpse of the proposed analysis, which takes its origin in the Aubin's viability theory [18]. Basically, if we denote as $\mathbf{F}$ the set of values of q where the system is considered as having fallen, we can say that a state $(q, \dot{q})$ is **viable** if and only if the system is able to realize from this state a movement $q(t)$ which never reaches $\mathbf{F}$. The union of all possible viable states is the viability kernel, inside which the robot is required to stay. An indication of the effective stability could therefore be to measure the "distance" between the current state and the closest state in $\mathbf{F}$. Unfortunately, this is completely untractable in practice. Although nicely intuitive, this approach deserves therefore to be improved. A way of doing that is, first, to define the largest invariant set associated with a control law, which is the subset of the viability kernel in which a fall is effectively avoided thanks to the control law. An invariance margin can then be defined as the distance between the current state and the boundary of the largest invariant set. Finally, an adequate stability margin can be defined with the help of a Lyapunov function and, even more, can be approximately computed by solving a well-posed optimization problem. It should be noticed, nevertheless, that such an analysis doesn't take into account possible variations in the state of the contact set.
A full approach of walking stability in the most general case remains therefore an open question [70].

2.4 Synthesis of artificial biped locomotion

The goal of this section is not to achieve an exhaustive bibliographical review of biped motion control approaches, but to present the main general principles which are (or could be) used in the design of schemes for synthesizing the motion. In fact, the differences between control methods lie mainly in the way the desired motion of the system is specified and in the required level of accuracy in the description. In the following we discuss the two main classes of approaches, where trajectories are designed off-line or on-line respectively.

2.4.1 Use of predefined trajectories

The most popular approach for biped control design includes both the a-priori definition of trajectories to track and dedicated techniques of on-line adaption to cope with model uncertainties, obstacles and disturbances in order to prevent the robot from falling. Several methods can be used to compute the desired (also called *reference*) trajectories, denoted generically as the multidimensional time function $q_d(t)$ in the following.

2.4.1.1 Trajectories in the joint space

Reference trajectories are commonly defined in the joint space. Roughly, they can be either human-inspired or purely generated by a computer using various methods.
In the first case, an intuitive idea consists in using data issued from human motion analysis: either standard joint motion patterns found in the biomechanical literature or especially captured motions, under the form of time joint trajectories, cyclograms, phase portraits... However, in both cases, the data generally don't fit exactly the actual kinematics of the robot. Furthermore, we generally want to be able to perform motions which may differ from the recorded ones (change of velocity, of type of walk, of ground geometry, transient behaviors...). It is also desired to avoid storing large databases integrating all required experimental data. This is why many people, and in particular from the computer animation area, have developed methods allowing to adapt captured data to various types and sizes of humans and to modify the specified motions [86]. This often requires to adopt compact parameterized representations of data: wavelet, polynomial or Fourier approximations are the most widely used.
A second way of generating trajectories, valid in the case of cyclic motions, is to mimic the human rhythmic function, trying to replace the function of a **Central Pattern Generator** (see section 3). The idea is to design self-oscillating systems (i.e. without inputs, although the shape of the output be tunable through some parameters) from which can be derived synchronized periodic motions of the joints. This approach is generally used for generating gaits for multi-legged robots (quadrupeds, hexapods) or snake-like systems, but some works also address biped robots. The most known nonlinear oscillator is the Van der Pol equation:

$$\ddot{y} + a(1 - by^2)\dot{y} + c^2 y = 0 \tag{7}$$

from which many variations can be derived. Similar results can be obtained from a more biologically inspired point of view: the design of neural oscillators [142]. In that case, sets of artificial neural networks with possible open-loop sinusoidal excitation [213] are connected to generate plausible walking patterns. In some cases it is even possible to create a kind of feedback in order to cope with environmental variations or to improve stability [72].

Besides the previous approaches, which more or less directly rely on an observation of the way human solves his walking problem, a fruitful idea consists in considering a biped robot as a dynamical mechanical system to which techniques of numerical optimization or of optimal control can be applied. This can be linked to the fact that in nominal steady state

walking, humans minimize the rate of metabolic energy consumption by distance unit. From a strictly mechanical point of view, the underlying idea is to exploit in the most efficient way the cyclic conversion between kinetic and potential energies which is involved in walking. Ballistic motions and impacts play an important role in this framework. Obviously, searching for synthesis of optimal motion requires the knowledge of an accurate model of the system, mainly in its dynamical aspects.
From a general point of view an optimization problem firstly relies on a cost function to be minimized. In robotics, generally [183, 45], cost functions are built from the basic form

$$J = \int_0^T L(\tau, q, \dot{q})dt \tag{8}$$

with:

$$L = (1-\alpha) + \alpha\tau^T W\tau \tag{9}$$

where τ is the set of actuation torques, W a weighting matrix and T the temporal horizon along which the optimization is performed. The constant parameter $\alpha \in [0,1]$ expresses the relative weight which is given to the minimization of the time ($\alpha = 0$, T unknown) vs the minimization of torques ($\alpha = 1$). In that last case, which will be the only considered one in the following, T is fixed. It corresponds to the duration of either a step, a stride, a double or a single support phase according to the considered cases. It should be emphasized that the interesting issue is, like for humans, to finally minimize the energy consumption with respect to the elapsed *distance*, in order to improve the autonomy of the robot. Since this is not easily tractable from a dynamical point of view, where time is involved, a rather frequent approach is to fix both T and the step length.
Remark: *knowing that the derivative of the overall mechanical energy of a frictionless system is equal to the power of external forces and torques, it is also possible to try to minimize the integral of [80]:*

$$L = \tau^T W \dot{q}_2 \tag{10}$$

Finally, let us notice that it is sometimes interesting to include in the cost function a so-called final cost, under the form $J' = J + f(q(T), \dot{q}(T))$. This may for example leave some flexibility in continuity conditions on the state variables during change of phases [80], which is less constraining than the following issues.
The minimization problem has now to be completed with initial/final conditions and constraints. Initial and final conditions concern the state and can be more or less completely fixed. Usually, conditions on positions should ensure the periodicity and the symmetry of the walk; velocities can be left free or a combination of some of them fixed if for example it is desired to have a smooth foot landing.
Contrary to the final cost or to previously evoked conditions, constraints are defined along the whole optimization horizon. They may concern state variables as well as control inputs. They are of two types:

- *equality* constraints. The first of them is of course the dynamics itself (eq.(1)), including or not impact equations eq.(3) according to the addressed problem. Closure equations of type eq.(2) may also be involved, for example in double support phase or when climbing a known stair. Position-based equality constraints are also a way of imposing a kind of synchronization between the motions of the links, by specifying the invariance of some combinations of joint variables. Coordinate change at landing time have also to be included in the problem statement.

- *inequality* constraints. They are generally used to characterize feasible motions. From a practical point of view, intrinsic limitations have to be considered in all cases, like joint limits as well as actuator bounds. Practical issues, like foot clearance during the swing phase or avoidance of an obstacle of known shape, can be expressed under the form of inequality constraints on joint positions. Another set of inequality constraints can be derived from conditions on normal and tangential contact forces (see section 2.2.1): no sliding, no ground penetration or no unauthorized take-off.

Once all the elements of the optimization problem have been defined, it remains to select a method of resolution. Let us recall that the goal is to find both a set of parameters p^* (some initial/final conditions, transition time between double support and swing phases...) and an open-loop control $\tau^*(t)$ $t \in [0, T]$, which result in an optimal time joint trajectory to be tracked later. Two main approaches can be considered for solving this problem. The first one is to directly apply numerical optimization algorithms to the specified problem, with as drawback the absence of guaranty of true optimality of the solution. This method will be used in section 2.4.2. In order to transform the problem into the optimization of a finite (even large) set of parameters, a discretization method is required. This can be a classical time-discretization using an Euler scheme with the assumption of a piecewise constant control. Another possibility is, like in the case of recorded human motions, to parameterize the involved variables through the development in series of functions, the approximation by polynomials... in temporal or frequential spaces. The numerical resolution can be finally performed using the efficient algorithms of Sequential Quadratic Programming implemented in easily available routines.

A second approach consists in going further in the mathematical development of the problem. Again two tracks are possible.

- one possibility is to use the classical variational calculous. In a first step, equality constraints, gathered into the expression $h(q, \dot{q}, \tau) = 0$, are included into L through the constitution of a Lagrangian:

$$L' = L + \lambda_1^T h \tag{11}$$

  where λ_1 is the array of associated Lagrange multipliers. Note that the previously evoked introduction of a final cost in J is another way of including some equality constraints. This can be extended to, for example, some initial conditions, by adding to J the adequate term through a penalty coefficient. In that case it is admitted that all these constraints cannot be driven exactly to zero since they take part to the minimization. Once this step is completed, the variation of the extended cost function, denoted as J', can be computed. This leads to a set of coupled differential equations in the state $(q, \dot{q})$ and the Lagrange multipliers λ_1. To these equations are attached initial and final conditions respectively. It is therefore a two-point boundary problem which requires an iterative solving with successive forward and backward numerical integration. Besides, the gradients of J' with respect to optimization parameters p and control variable τ can be computed and used jointly with the differential equation solving in some descent method, like conjugate gradients.

- another approach is based on the popular Pontryagins'maximum principle, developed in the framework of optimal control. Its principle is the following: writing the dynamics under the classical state form $\dot{x} = g(x, \tau)$, x standing for $(q, \dot{q})$, we can define a so-called Hamiltonian:

$$H = -L(t, x, \tau) + z^T g(x, \tau) \tag{12}$$

  where z, called adjoint state, plays the role of Lagrange multipliers. The necessary optimality conditions are then:

$$\forall t \in [0, T] \begin{cases} \dot{z}^*(t) = -\frac{\partial H}{\partial x}^T(t, *) \\ \dot{x}^*(t) = \frac{\partial H}{\partial z}^T(t, *) \\ \frac{\partial H}{\partial \tau}(t, *) = 0 \end{cases} \tag{13}$$

  $*$ meaning that all variables are to be taken at the optimal solution.
  The last equation means that the optimal control $\tau^*(t)$ corresponds to a maximum of the Hamiltonian. As previously, these equations come with initial *and* final conditions which require, for example, the use of shooting methods for solving.

To conclude on this class of methods for trajectory generation, let us mention that they could also be used to optimize the robot structure itself by including in the parameters to find, trough the minimization process, some physical issues: link mass distribution, lengths,... A last thing is that obtained trajectories should not be considered in practice as the true optimal ones, as used models are always unperfect, and the later introduction of a control scheme may result in a nonoptimal behavior: for example it can be more expensive to use energy to accurately track an "optimal" trajectory than to leave some freedom to the system.

2.4.1.2 Trajectories in other spaces

When there is no particular reason to specify trajectories in the joint space, it is often interesting to use another type of space, an element of which is denoted as $e(q, t)$, which can be seen as an **output space** in the sense of automatic control, the dynamics having then the meaning of state equations. For example, it is easier to specify what should be the trajectory of some points on the foot (heel, toes) which allow to avoid an obstacle on the ground than expressing the same objective in the joint space. More generally, specifying

explicitly what is the desired trajectory of the Center of Pressure is a way of expressing some practical stability requirements.
Many types of equality or inequality constraints evoked previously can be intuitively expressed in that way. For example, when setting velocities and accelerations equal to zero, choosing as a constraint the position of the CoM in such a way that static stability is ensured, and fixing the position in the 3D space of some links, allow through the numerical optimization procedure previously evoked to find statically stable postures [32, 133, 19].
A last point which deserves to be emphasized is the fact that exteroceptive sensors which measure local interaction with the environment (proximity, distance, contact force) can be directly used in a dedicated output space without further signal transformation.
From a control point of view, it is worth noting that the specification of a tracking objective in an output space allows to use the dedicated task-function approach [37] for driving $e(q,t)$ to zero. A drawback of all that is the fact that, like for manipulators, singularities may appear, even if explicit inverse kinematics is not required. Another point is that input and output dimensions may differ, which requires to exploit the induced redundancy, like evoked at the end of section 2.3.1.

2.4.1.3 On-line adaptation

Once a trajectory $q_d(t)$ to follow has been defined, whatever the used method and the chosen workspace, it is necessary to design a control scheme allowing to track the trajectory as accurately as possible. Basically, a proportional-derivative loop on the tracking error is the core of the control scheme [19]. However, since the use of high gains is not always desirable due both to the presence of noise and to the need of discretization, good tracking performances require the integration of additional issues in the control. When the dynamics of the system is well known, it is often interesting to use it, in a so-called computed torque approach, in which the applied control torque is of the form (here in the joint space):

$$\Gamma = \hat{M}(q) * (k_p(q - q_d) + k_v(\dot{q} - \dot{q}_d)) + \hat{N}(q, \dot{q})\dot{q} + \hat{G}(q) + \ddot{q}_d + ... \qquad (14)$$

where the hats mean that more or less accurate models are used (feedforward control). At least the compensation of gravity term $G(q)$ should be considered. One of the most important source of errors is the effect of friction. As soon as an effective model of friction, in joints, gears and actuators is available, it should be used, of course with care. Many variations around this scheme exist, for example the linearization of the dynamics, or the use of an inverted pendulum model. Nevertheless, although this kind of control can cope with some internal disturbances, it is neither sufficient to ensure in real time the stability of *walking* in a robust enough way nor to cope with environmental uncertainties. The basic requirement is now to find a way of controlling the ground contact forces in order to be sure that the support foot (or feet) remain motionless when it is specified and/or needed by the reference trajectory. This means that the control has to ensure that the inequality conditions (no sliding, no take-off) which involve the Lagrange multipliers as stated in section 2.2.1 are verified at each time despite disturbances. Of course this capacity of reaction will be limited by the bounds which exist on the actuators.

A popular way of addressing this question is to split the control into two parts [132, 124]: a first one, which is devoted to the tracking of the prescribed trajectory, involving a large subset of the joints; a second one which is dedicated to the control of the ground forces through selected joints: trunk, or more often, ankles. It can be shown that controlling ankle torques is a way of approximately control ground reaction forces through an adequate compliant model. The design of the control can be done using the previously evoked inverted pendulum approximation. The implementation can use more or less directly force/torque measured by sensors in the ankle or the sole. Another way of controlling the balance is to use a direct feedback of the total angular momentum in the control of ankle torques [116]. Although these approaches have demonstrated some efficiency, they suffer from a lack of genericity. An interesting attempt to derive a systematic way of online adapting (see section 3) the behavior of the system consists in adding degrees of freedom to the definition of the trajectories to track by parameterizing them [209, 211]. The principle of the method is the following: let us consider that, in fact, the reference trajectory depends from a set of time-varying twice differentiable parameters p: $q_d = q_d(p(t))$. In p may appear various characterizations of the trajectories: step length, maximal height of the heel trajectory, etc... even including a possibility of time scaling in order to speed up or down the motion. These parameters are set to a nominal value p^* corresponding to the desired motion. However, since they are supposed to evolve when needed, it is necessary to set their dynamics of return to p^*, through a linear second order behavior $\ddot{p}_d = f(p, \dot{p}, p^*)$. Now, it can be shown that is it possible to gather the dynamics including a PD control scheme like in eq.(14), the unilaterality of contacts, the requirements of non-sliding and no take-off, and the bounds on actuators, all described in section 2.2.1 and summarized in equation (6), in a single vector inequality of the form:

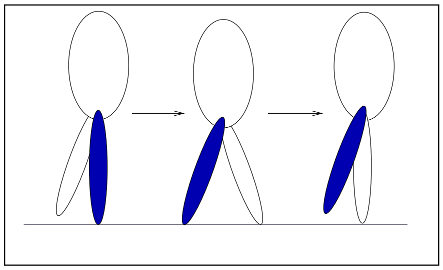
$$\mathbf{L}(q, \dot{q}, p, \dot{p}, \ddot{p}) \leq 0 \tag{15}$$

The problem is now to be solved by finding at each time through an adequate optimization method the parameter acceleration $\ddot{p}$ which minimizes $||\ddot{p}_d - \ddot{p}||^2$ while ensuring that (15) is satisfied. This approach is, for example, able to compensate for disturbances like external forces applied to the body, since they reflect at the internal state level, and are therefore accounted through the respect of the inequality (15). It has been shown [211] that it is possible to increase by a factor ten the range of acceptable disturbances with this method, compared to non-adaptive ones. Furthermore, the use of exteroceptive information like distance, proximity, vision is allowed since they may generate directly a modification of the parameters, for example to climb a stair or to avoid a hole, even though the detection is performed online.

2.4.2 On-line synthesis of the motion

2.4.2.1 Inspiration from passive walking

Historically, a first attempt to tackle the problem of biped locomotion synthesis was to exploit the concept of passive walking [144, 89], following earlier studies on hopping systems [177]. Let us consider the simplest possible walking system, a compass with pin-point feet



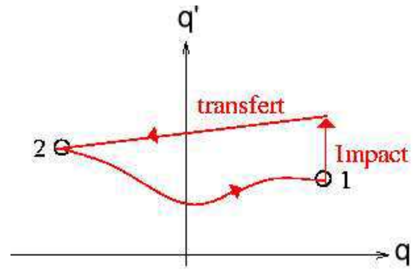


Figure 3: A simple compass model

(fig.3). Once constrained to stay within a vertical plane, this single-joint system has a 4-dimension configuration space. Let us now place it on a plane slope in such a way that it moves by itself, without any further actuation, like some toys, and make some assumptions:

- the gait consists of two stages: a swing phase during which the robot hip pivots around the support point, supposed to stay motionless; a transition phase, which occurs instantaneously, when the swing leg touches the ground and simultaneously the previous support leg leaves the ground;
- the impact is assumed to be slipless unelastic. This implies that at the transition the configuration remains unchanged, while angular momentum conservation leads to a discontinuous change in velocities.

Consequently, the robot behavior can be fully described by a 2D state (position and velocity of the hip joint), the dynamics of which is of the form (1) with a second member equal to zero for the flight phase, and with an impact model as described in section 2.2.2. Due to its low dimension, an adequate study tool of this system is the phase portrait, i.e. the evolution of orbital trajectories $(q, \dot{q})$. The stability of these orbits can be studied through the Poincaré map. It can thus be shown that, for some sets of slopes, mass distributions and initial conditions, the system reaches freely an asymptotically stable orbit, which results from an optimal balance of the energies involved in the system: transformation between potential and kinetic ones, loss at impact. The overall mechanical energy, which is constant, is a characteristic of the obtained walk, which corresponds to a kind of "energetically optimal comfort gait" for the system. This trajectory is in fact found by the robot itself thanks to the laws of mechanics. It can be shown that increasing the slope leads to phenomena of period doubling (bifurcation), followed by a chaotic behavior and then by a fall if the descent is too steep.
This idea has been later largely exploited, first by adding more joints (knees, trunk, feet), springs, masses, still in a purely passive framework [48]. But the idea to extend the approach to actively controlled systems appeared also as an interesting track [12, 154]. The principle is to design a control which mimics the behavior of a passive system, i.e. the convergence towards an optimal stable orbit, even in the case of non descending planes. Another advan-

tage of a well-designed control lies in the possibility to extent the basin of attraction of the stable orbit. Nevertheless, despite their interest, all these approaches are difficult to apply to 3D real systems with several degrees of freedom, complex ground contact models, etc... It should however be noticed that the idea of studying the behavior of the system through its orbital stability has also been successfully used in the design of the control of the robot Rabbit [170, 46, 207]. This planar 7 DoF robot presents an underactuation of degree 1, therefore a zero dynamics, the stability of which can be assessed using a Poincaré map.

2.4.2.2 On-line optimization

The ultimate way to adapt in real-time the motion of the robot is to even avoid using any type of pre-computed trajectories. Among the candidate approaches to this kind of on-line motion synthesis, the so-called **Model Predictive Control (MPC)** techniques look well-suited. The common underlying idea is the following. Let us firstly assume that we have got a dynamical model of the system good enough for synthesizing a control scheme. Then, the principle of the method consists in performing *at each sampling time* the following operations:

1. measurement of the actual state;
2. computation of the control which optimizes a given state-dependent cost-function on a finite horizon, starting from the current time;
3. application of the first computed control inputs only;
4. return to step 1.

Historically, this approach has been applied to large systems, like chemical plants, the dynamics of which were slow enough to be compatible with the required optimization time. The exponential growth of available computer power at constant cost made it possible to progressively extend the domain of application of these methods to more rapid processes. The bottleneck remains nevertheless the availability of theoretical results of stability, which is now limited to linear systems or particular classes of nonlinear ones. The **Nonlinear Model Predictive Control (NMPC)**, associated with this last case, has some ability to handle constraints, which makes it well suited to the problem of walking pattern synthesis and control of a biped robot subject to unilateral constraints or disturbances due to an unstructured environment. A complete overview about theoretical and practical results concerning the MPC or the NMPC can be found in [7]. However it can be seen from these papers that the straightforward application of the algorithms is very limited when dealing with highly dynamical systems such robots. In fact, most of the assumptions required to guarantee stability are not tractable. Furthermore, this technique has been developed in a reference trajectory framework. Some modifications of the approach are therefore required for the application to on-line walking synthesis. Following the idea of the parameter adaptation method presented earlier §.2.4.1.3 which solves at each time an optimization problem, the **Trajectory-Free Nonlinear Model Predictive Control (TF-NMPC)** [20]), is based on a constrained optimization problem with a moving horizon. Moreover, a set of constraints g is imposed in order to ensure feasibility of walking. Defining these constraints is the only way which is used to express implicitly the desired motion of the robot. A qualitative example of such possible specifications, in the case of steady-state normal walking in the sagittal plane is, for the swing phase:

- *physical limits: the control torques belong to a given set; the range of joint values is bounded*
- *stability: normal contact forces are strictly greater than given positive values; the absolute values of tangential forces are less than given thresholds linked to friction parameters*
- *forward progression: the horizontal velocity of the ankle of the swing leg belongs to a given interval; the horizontal position of the pelvis stays inside the position of the toes of the support foot and the horizontal one of the heel of the swinging foot*
- *posture: the angle expressing the trunk bending is positive and bounded; the angle between the sole of the swing foot and the ground is fixed; the height of the pelvis is low-bounded;*
- *foot clearance: the vertical position of the ankle is constrained to stay inside a given area (for example specified by two polynomial functions of its horizontal position). These functions are a way of avoiding obstacles or climbing stairs.*

Thus, the TF-NMPC consists in optimizing, from the inputs (control, state, contact forces...), the anticipated future behavior of the system, subjected to constraints, using an internal model over a finite sliding time horizon. The TF-NMPC is finally termed as the following open loop constrained optimization problem that is solved at each sampling time:

$$\begin{array}{rl} & \min_{u_k^{N_c}} J(x_k, u_k^{N_c}) = \Phi(x_{N_c|k}) + \sum_{i=0}^{N_c-1} L(x_{i|k}, u_{i|k}) \\ \text{subject to:} & x_{l+1|k} = f(x_{l|k}, u_{l|k}) \\ & x_{0|k} = x_k \\ & g(x_{l|k}) \leq 0 \\ & u_{l|k} \in \mathbf{U},\ l \in [0, N_c - 1] \\ & x_{l|k} \in \mathbf{X},\ l \in [0, N_c] \\ \text{with:} & \mathbf{U} := \{u_k \in \mathbb{R}^m \mid u_{min} \leq u_k \leq u_{max}\} \\ & \mathbf{X} := \{x_k \in \mathbb{R}^n \mid x_{min} \leq x_k \leq x_{max}\} \end{array} \tag{16}$$

where:

- $s_{i|k}$ is a notation meaning that the variable s is predicted at the current time k. The index i indicates the prediction time controller starting from k,
- u_k and x_k are respectively the input and the state of the system,
- $x_{i|k+1} = f(x_{i|k}, u_{i|k})$ is the nonlinear dynamics model,

- J is the objective function to minimize composed of a cost function L depending on state x and input u,
- Φ is a weighted factor depending on the terminal state over the horizon introduced to guarantee stability [7, 143],
- **U** is a set of input constraints,
- **X** a set of state constraints,
- $g(x_{l|k}) \leq 0$ define the set of inequalities characterizing the physical walking motion constraints.

The solution of the optimization algorithm is a sequence of N_c control inputs over the prediction horizon N_p. Only the first input is applied to the system and the procedure starts again. It should be noted that the feedback effect which should be included in any real-time control appears through the use of *actual* current values of the state in the optimization. Furthermore, the adaptation of the motion in order to react to unexpected events can be performed by modifying on line the set of equality and inequality constraints (fig.4).

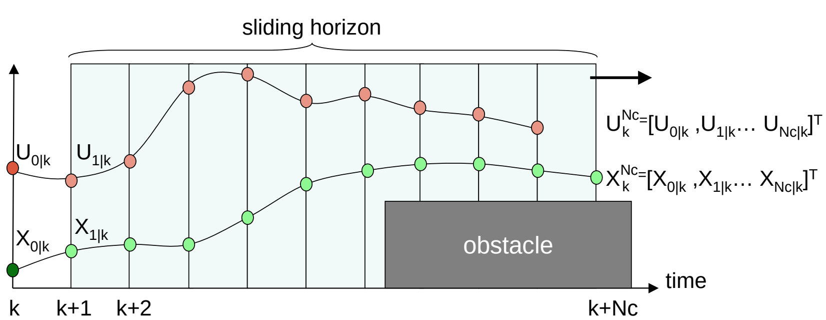


Figure 4: NMPC principles

3 How does human walk: a functional description

Regulation of human walking should be an excellent example for robotics since human could be considered as the “ultimate robot". It is especially important to learn about some of the features which make human displacements such efficient, automated yet highly adaptable [70].

We will not describe here walking structure since many works exist on the topic, the reader is referred to: [6, 40, 82, 182, 200, 208, 215, 221]. We will focus our attention on the architecture of the controller and the mechanisms involved in the achievement of biped displacements.

On the past decades, experimental studies on human locomotion were mainly focused on the effectors, i.e. the limbs less on the multi-joint and segmental strategies. Central controller, i.e. the brain, has classically been investigated in animal studies (for review, see [67]) and in humans with clinical studies. Thus, only indirect observations in human pathologies were available as regards the central structures responsible for human locomotion. Recently, the brain was investigated during locomotion in healthy subjects with TMS (Transcortical Magnetic Stimulation) [38, 39, 168]. Moreover, ankle dorsiflexion as an fMRI (Functional Magnetic Resonance Imaging) paradigms to assay motor control for walking as been proposed [61]. Walking is not feasible during fMRI but has been performed during near-infrared spectroscopy (NIRS) [153, 152], fluorodeoxyglucose PET [60], and single photon emission computerized tomography [81]. This hierarchy in the interest taken in the various components of bipedal locomotion that we will analyze below results in corresponding difficulties for experimental approaches. Indeed, if analyzing activity of the effectors, the kinematics and the dynamics of movements have been facilitated thanks to various new and efficient tools such as electromyography, force-plates and optic-electronic analyzers with low constraints for the subjects. The moving brain is still not compatible with imaging measurements. Only indirect observations in human pathologies are available up to now as regards the central structures responsible for human locomotion.

Our attempt in this paper is to raise the main features available in the literature and resulting from our own works concerning human behavior and to express them from a functional point of view as basic principles which should benefit to future anthropoid robot controller design. We use on purpose vocabulary from automatic control and robotics to describe them.

3.1 Principles of the postural control

3.1.1 Postural orientation and postural stabilization

Posture is usually defined as the relative position of the various parts of the body with respect to one another and to the environment. But posture is above all an active control as it is necessarily obtained by a muscular activity to fight against gravity. We will define the posture through two components: orientation and stabilization. The postural **orientation** (or configuration) of the body parts corresponds to the organization of the body segments with respect one to another but also with respect to an external referential (§.3.1.3). Redundancy plays an important role as there exists several configurations to reach a same objective. The postural **stabilization** (or balance) of the configuration consists in maintaining actively by muscle contractions and elements of movement the chosen postural configuration against external or internal disturbances or the inaccuracy of biological signals and commands. Redundant and complementary sensory information inform the system about errors and drifts of the actual posture in comparison with the desired one. In scuba diving or in microgravity, without any voluntary movement, only orientation component is present and there is no external force to disturb the posture.
Actually, the postural control system is involved in the control of these two behavioral goals,

both necessary to provide a stable body platform for the efficient execution of movements [104, 158, 9]. Orientation and stabilization are probably controlled independently [9] by distinct mechanisms as regards the implied neural networks [166] and the frequency domain of used sensory error signals [9, 8].

3.1.2 Postural and locomotor equilibrium

A major problem for human standing posture is a high center of mass (**CoM**) maintained over a relatively small base of support. The body has therefore a high potential energy leading to priority of equilibrium control during all motor tasks.
Balance is not an isolated function and it cannot be separated from the action of which it is an integral component, or from the environment in which it is performed [107]. It requires control of both gravitational and acceleration forces, in order to maintain respectively posture and equilibrium. Acceleration forces may be generated within the body voluntary movement or from an outside disturbance, such as a push.
Balance control consists in maintaining the body center of mass (CoM) within manageable limits of the base of support, as in standing, or in defining a new base of support, as in walking or running.
Postural equilibrium (i.e. balance, i.e. stability) is a state in which all the forces acting on the body are controlled, so that the body rests in an intended position or is able to progress through an intended movement without losing balance. In quiet standing, postural balance, classically called **static equilibrium**, corresponds therefore to the definition of mechanical equilibrium: the system is in a state where the sum of the forces and torques applied to it is equal to zero. Balance in walking does not cope with this definition, since the center of mass is lying outside the base of support for 80% of the gait cycle. It is abusively called **dynamic equilibrium**, and there is no strict definition to express the fact that the body moves without falling.
Equilibrium control relates to maintaining intersegmental stability of the body and its parts despite the forces acting on it. Forces induced by linear and/or angular accelerations affect the relationship between body parts. For example, the angular acceleration acting at the shoulder when raising an arm creates reactive moments on the trunk which must be countered by opposing postural moments before and during the movement [73].
Similarly, horizontal acceleration forces occur at the hip during walking. Because they act at some distance from the center of mass, they cause unbalancing moments that would, if unopposed, cause flexion of trunk at initial contact and extension during push-off [216]. In order to prevent this, the balance system produces almost equal and opposite hip moments, reducing antero-posterior movement of the trunk.
The activity undertaken determines the magnitude, direction and combination of the forces of gravity and acceleration, changing its biomechanical parameters throughout the task. Environmental context of a task can also alter its biomechanical parameters: walking surfaces induce accommodation of walking kinematics and kinetics and modification of balance strategies. Obstacle avoidance strategies are also an environmental effect on motor and balance [107].

3.1.3 Spatial reference frames and segmental stabilization strategies

To accurately maintain postural as well as locomotor equilibrium, the postural system relies on **stable reference frames**. These frames may be either external (exocentric) like the gravity vertical or the horizontal ground, or internal (egocentric) if they concern the body. In the latter case, they may be either global (i.e. concern the whole body) or related to a single body segment. Indeed, each body segment (either moving or stationary) can constitute a spatial reference frame for another segment and/or the whole body. The head, for instance, may be referred to the trunk through the neck signals, which code both velocity and position of the relative head-to-trunk rotation [11, 148], but the head may also be referred to the vertical gravity force via vestibular signals. As an example of egocentric frame of reference, the orientation of a given body segment such as the head, trunk and forearm serves as reference frame for calculating the position of objects in the surrounding space and for planning the appropriate hand trajectory for reaching and grasping [191, 141].
An important aim of the human postural control is therefore to insure the stabilization with respect to space of a given body segment, which will be used as a spatial reference frame for movement programming or postural stability, namely to adopt the appropriate strategy of segmental stabilization [15, 112, 10].
Standing and walking activities are organized on the basis of two types of stable references: the support on which the subject is standing and the gravity vertical. In the case of a steady contact, the surface on which the subject is standing constitutes an exocentric frame of reference used for postural control, the feet are anchored and referred to the stable earth surface by gravity via pressure receptors in the plantar sole [88]. The subject relies mainly on the proprioceptive and cutaneous information conveyed by the effectors and temporally organizes his balance control upwards from the feet to the head in a **ascending organization**.
In the case of intermittent contact, it is necessary to stabilize, on the basis of the gravity vertical, at least one anatomical segment which then constitutes the reference value. There is a need to transfer the reference frame from the support to an angularly stabilized body segment, such as the head or the pelvis [15]. The spatial orientation of the head may thus have to be maintained in order to serve as an egocentric reference value for controlling the locomotor equilibrium or the movement trajectory [26, 24]. The choice of the stabilized segment presumably depends on the dynamic constraints, which define the difficulty of the postural or locomotor task. It may be either the hip, at about the level of the center of mass, or the head which carries the vestibular system. *The stabilized segment constitutes the origin of the temporal organization of balance control.* The subject relies on the vertical pull of gravity in order to stabilize either the pelvis or the head, on the basis of local information about gravity. The subject then stabilizes his head in space mainly on the basis of vestibular information and temporally organizes his balance control working downwards from the head to the feet in a **descending organization** [15].
The use of spatial frames of reference implies the ability, for the central nervous system, to build up and utilize internal representations of the body in space, that we will consider below (§.3.3.3).

3.1.4 The trunk, leader segment of human locomotion

Human locomotion is mainly organized towards the control of the trunk, due to its mass, and we can say that human walks primarily with his/her trunk, the limbs following it (or not, in which case the walker falls). Indeed, falls can be the result of an inability of the effectors to rapidly respond to more or less uncontrolled movements of the trunk mass. Similarly, we can say that braking and stopping locomotion are behaviors that are less induced by the limbs than by the trunk itself. Due to its mass (over 40% of the total body mass), the trunk has a privileged role in equilibrium maintenance, and thus appears to be the main segment both for eliciting and stopping locomotion.

These particular skills have to be learned during human ontogenesis, because of the growth of the musculo-skeletal system that has to be integrated in the body scheme and because of the progressive maturation of the central nervous system.

In fact, human trunk is not a single solid segment, but rather a superposition of several ones, at least two in the lateral plane, the third lumbar vertebra (L3) being the main pivot of the lateral spinal movements [165]. During bipedal locomotion, the difficulty of maintaining equilibrium is accentuated by the fact that the weight of the whole body has to be supported by one leg at a time during the swing phase of gait, during which vertical projection of the CoM remains out of the supporting surface. This could induce destabilization of the trunk towards the swing leg, which is in fact partly avoided thanks to appropriate postural adjustments, the residual destabilization being then overcame by the contact of the swing leg with the floor. The main feature of lateral movements of the spine while walking is then a clear stabilization in space of the upper trunk (above L3), associated with a descending temporal organization of the lateral trunk movements, suggesting an anticipation of the imbalance due to the intermittent foot contact with the ground (feedforward process) [195, 156].

Before the building up of such anticipatory movements during ontogenesis, children rather display a hip-centered organization of lateral balance control during locomotion, suggesting only an anticipatory activity only at the pelvis level with respect to the feet movements associated with a reactive activity (feedback process) of the upper part of the body with respect to the pelvis [16, 15, 17]. This reactive behavior of the trunk in walking children does not yet insure economy of energy expenditure that will be observed later-on in adults. The constant feature across life span is in fact the pelvis stabilization in space while walking, which appears from the first week of autonomous walking. This early pelvis stabilization in space is presumably aimed at minimizing the lateral movements of the center of mass (CoM) and avoiding fall of the hip towards the swing leg [214, 135]. The stabilization of the hip seems to be a prerequisite for autonomous walking in toddlers.

As regards horizontal movements (about a vertical axis) of the spine in walking adults, they also show a temporal descending organization from the shoulder downwards, due to the oscillating arms, whereas horizontal movements of the pelvis are initiated by the stepping movements at the feet level [51].

3.1.5 The limbs, effectors of locomotion

The question of whether or not control of human gait is based on a quadruped locomotion system has been recently addressed [56]. Recent research indicates that interlimb coordination during human locomotion is organized in a similar way to that in the cat [58]. The authors have suggested that, in humans, the proximal arm muscle responses were associated with the swinging of the legs during gait, as a residual function of quadruped locomotion. Some other comparisons may also be made. In quadrupeds, when one leg becomes unsupported, a diagonal stance takes place, whereby the body support is provided by two diagonally opposite limbs, without displacement of the CoM [109, 83]. Although there are obviously notable differences between walking with two or four legs, comparable quadruped organization and diagonal pattern can be observed in human locomotion.

Nevertheless, an important difference between both types of displacements is that while initiating locomotion, human subjects have to firstly transfer their weight over the supporting leg before lifting the oscillating one. It should be noted that mechanical sensors in the extensor muscles of the **legs** provide the central nervous system with information liable to contribute to this motor programming. Extensor load receptors are thought to signal changes of the projection of body center of mass with respect to the feet [55]. A second difference is that while walking, the vertical projection of the CoM in bipeds remains most of the time out of the supporting base. This is part of economy expenditure, since walking biped can allow lateral fall (CoM projection out of the supporting surface) towards the oscillating leg during single support phase. However, during steady state locomotion, a kind of diagonal pattern may be observed in the gait cycle, since the forefoot of the supporting legs produce forward and vertical impulse, after what the oscillating leg firstly contacts the ground with the heel. This mature pattern has also to be acquired during ontogenesis, since in the locomotor pattern during the newborn period (6- 12 months of age) the foot is placed on its forepart straight under the body before being later a plantigrade pattern of locomotion [78]. Moreover, it should be noted that, due to the mechanical properties of the heel pad, there is some energy loss during a cycle of compressive loading and unloading. In fact, the springy heel pad may help to reposition the foot during the transfer of load from the heel to the forefoot [121].
Each foot is an articulated segment, composed at least of two parts, the anterior one including toes and the heel [85], providing with a mechanism for changing the gear ratio of the ankle extensor muscles during a running step for instance [41].

Although they no more directly contribute to propulsion, as it is the case in quadrupeds, the **arms** (upper limbs in quadrupeds) may help both efficiency and equilibrium control in the performed movement during various kinds of human displacement. For instance, the added balance and control provided by the arms throughout the jumping motion largely improves jumping distance in the standing long jump [13]. During normal locomotion, there is a clear coordination between arm and leg movements [63, 204]. According to Wannier et al. [205], the characteristics of the coordination between arms and legs correspond to those

of a system of two coupled oscillators as that underlying quadruped locomotion. Moreover, the loading of one arm, which occurs naturally while carrying some heavy object, induces a general reorganization, involving all participating anatomical segments, presumably to maintain balance while providing rhythm constancy [64].
It is not clear whether or not arm movements associated to human locomotion contribute to energy consumption, since arm immobilization does not increase energy expenditure during level walking at comfortable walking speed [98]. According to Jackson [113], controlled upper limb movement would be a necessary component of smooth non-jerky locomotion. Another study have suggested that, during normal-speed walking, arm-swing and vertical free moments (force couples in the horizontal plane between the foot and the ground) tend to reinforce each other in balancing trunk torques induced by the lower limbs, whereas both are of reduced importance in slow walking [131]. In the case of an unexpected slip at ground level, the reactive recovery response consists of a large arm elevation strategy [139]. This observation demonstrates the utility of rapid arm movements, easier than those of the trunk due to the lower inertia of the limbs as compared to that of the trunk, in compensating for locomotor imbalance. This arm response also reflects the fewer constraints imposed upon the actions of the arms, compared to the legs, during normal locomotion [138]. Thus, the arms seem to have mainly a mechanical contribution to movement execution rather than an energetic one.

3.1.6 Role of the head

As already mentioned above, the head angularly stabilized and anchored on the gravity gravity constitutes the reference frame which human [94, 26, 16] and animal [179, 66, 196] locomotion are referred to. This segment has therefore to resist to disturbances induced by locomotor movements rather than to follow them. In response to a movement liable to disturb the postural or locomotor balance, the organism will thus predictably attempt to minimize the head angular movements induced by the trunk oscillations, thanks to sensory receptors that specify head orientation relative to gravity (vestibular otoliths), head motion (otoliths and semicircular canals) and head position with respect to the environment (eyes). Similarly, when gaze stabilization towards a visual target is required, angular head movements in pitch act in a compensatory fashion to oppose the vertical trunk translation that occurs during each step in the gait cycle [171]. These strategies of head (or gaze) stabilization in space (or on the visual target) during locomotor movements are thus mainly aimed at improving the processing of the sensory feedback from the head (visual and/or vestibular) required for balance to be maintained or reaching to be adjusted.

3.2 Hierarchical control architecture

A remarkably complex system exists in human abilities to initiate, coordinate, and integrate the ongoing control of muscular contractions that result in actions. Proper control of movement involves: 1) the **accurate timing and coordination** of commands to multiple muscle groups, 2) an **on-going monitoring** of the current position of the body and the distribution of its mass to allow for making necessary adjustments, and 3) the **integration of constraints** imposed by the unique physical characteristics of the body and muscles (such as inertia, resistance, and muscle stiffness). The motor system accomplishes these difficult processes by dividing the control into smaller more manageable subtasks, with separate structures executing each subtask. The smooth synthesis of these tasks by the central nervous system frees us to focus attention on a large part of our movements or environment. The motor control system is a hierarchical, decentralized controller that consists of several subsystems over which subtasks and commands are distributed [117, 71]. A modular organization at functional levels has also been suggested in human capabilities in manipulating many different tools with dexterity [108, 100, 119]. Constraints from task and environment affect motor performance by altering biomechanical features of the activity and affecting the amount of information that must be processed in order to achieve both balance and motor goal. Concerning the control of standing in human, Pérennou et al. have suggested a predominance of the right hemisphere for controlling body stabilization while the left hemisphere controls motor skills [167] (§.3.1.1). This **specialization of brain parts** could optimize the allocation of brain resources. But this speculation still remains a matter of debate.

3.2.1 Hierarchical organization of the central nervous system

The so-called **central nervous system (CNS)** consists of the brain and spinal cord, it can be seen as a complex hierarchical controller [198]. One motor task is broken down into several subtasks and commands which are distributed over different subsystems [36]. The **motor cortex** performs at the highest level in the hierarchy control, it is concerned with conception of actions and strategies. The **cerebellum** and **brainstem** operate at the middle level, dealing with tactical planning to carry out the movements needed for a given strategy. **Spinal cord** is the lowest level, which is concerned with the actual execution of movement and the ongoing monitoring of sensory information coming from the muscles and joints (i.e. peripheral nervous system (PNS)). All the commands from the higher levels are coordinated into properly timed commands for the muscles. Higher levels of the system project downward to influence sequentially activities of lower levels. Even though a direct analogy between CNS and a computer is attractive, human brain cannot be compared to a physical machine since it has to primarily build locomotor behaviors among many other ones during ontogenesis, while progressively ensuring in parallel its own maturation. Hierarchy plays a key role in human motor control and learning [101]. We can generate a variety of structured motor sequences such as writing or speech and learn to combine elemental actions in novel orders. This suggests that high-level representations may exist and that the lower levels are concerned with compensating for different dynamics.
It has been proposed that the cerebellum incorporates various kinds of internal models, which emulate the external world by learning from experience [218, 118, 77]. They enable us to act quickly and appropriately by predicting the future. Most previous research on internal models focused on pure motor control tasks, but some results confirmed that in the cerebellum, there exist many internal models for highly cognitive tasks. Between the levels,

	Reflex	**Automatic**	**Voluntary**
Pathways	Spinal	Brainstem / subcortical	Cortical
Activation	External stimulus	External stimulus Internal commands	External stimulus Self-generator
Response	Local to stimulus appli -cation and stereotyped	Coordinated and stereotyped	Variable
Role in balance	Muscle force regulation	Resisting disturbances	Purposeful movements
Latency (leg level)	Fixed 35-45ms	Fixed 95-120ms	Variable >150ms

Table 1: Properties of movement control mechanisms [120]

there should be a vertical bidirectional connection, passing responsibilities upwards and priors downwards. Many of the recent anatomical and physiological findings are suggestive of such a structure within the cortico-cerebellar loops.

3.2.2 Movement control

Conversely to classical robotic techniques, human walking **coordinated movements are not generated by slaving to an explicit representation of the precise trajectories of the movement of each anatomical segment** but by dynamic interactions among the nervous system, the muscular-skeletal system and the environment [193]. Different types of movement exist and are associated to different types of commands. **1) Voluntary movements** are integrated at a cortical level and can be initiated without any external stimulus. **2) Automatic movements** are memorized strategies which are elicited by internal commands or external stimuli. **3) Spinal reflex** are genetically programmed responses to external stimuli which are modulated by superior centers. These different type of movements are characterized by latencies that can go from 150ms to 35ms (table 1).
The importance of sensory input for guiding movement is evident when analyzing the effects of damages to the touch receptors, muscle spindle system, or Golgi tendon organ. As an example, when proprioceptive information from the hand is absent, fine motor movements are seriously impaired and vision is essential to maintain proper positioning. As an other example, a totally deafferented patient appears to be definitely unable to walk and needs visual cues to initiating and controlling any voluntary movement [21, 30].

Two classes of control systems that differ in the way they use sensory input appear to control motor function.

1. **Feedback control**
Feedback control consists of a closed loop between motor commands and sensory information. It is used to execute skilled and accurately timed movements. It involves ongoing monitoring of the movement in progress by a “comparator” that matches the

actual movement outcome with the desired outcome, and makes the necessary adjustments to any errors or deviations from the expected program. This control loop is slow, continuous, and stops when the desired position is achieved.

2. **Feedforward control**
Like in machines, there exist delays in the human sensorimotor loops. If the processing of sensory information is long with respect to the duration of movement, the position of a given limb will change dramatically by the time the feedback signal starts to influence the ongoing motor command, thus rendering the implemented correction inappropriate. Behavioral experiments have shown that the minimum delay needed for a visual or proprioceptive signal to influence an ongoing movement is 80-100ms [114, 164] while that for the duration of a hand reaching movements is typically 300-700ms [53]. This has led to the proposal that movements are primarily under pre-programmed control and that sensory feedback loops exert an influence only at the end of a trajectory. Behavioral data suggest that a motor plan is assembled prior to the onset of movement and is updated continuously by internal feedback loops.
The concept of **motor program** might be viewed as a set of muscle commands that are structured before a movement sequence begins, and that allows the entire sequence to be carried out uninfluenced by peripheral feedback. Feedforward control [53] uses sensory information prior to the execution of movement, on the basis of an internal representation built up by means of previous experience. This type of control is used in the execution of rapid movements and is applied briefly and intermittently, when the planning of a new movement is required.

At the spinal level, the feedback can occur through specialized **reflex pathways** linking muscle sensors and motoneurones. Local reflexes at the limb level, supplied by sensory re-afferents, are also subjected to the influence of CNS which can modify the gains of these control loops [50, 68, 49, 174, 92, 35].
As in other vertebrates, there seems to be good evidence that the locomotor pattern can be generated at the spinal level [69, 59, 134, 57]. **Central pattern generators (CPG)** are neural circuits which can generate rhythmic activity without rhythmic input. CPGs are located in the spinal cord, and distributed in different oscillatory centers [93]. Both the CPG and the reflexes are under the control of the brainstem. Pattern generation is basically innate. In humans, step like movements are present at birth; they are spontaneously initiated or triggered by peripheral stimuli. A central origin of these movements is implied, as an electromyographic (EMG) burst preceding the actual mechanical events [78]. Voluntary commands have to interact with the spinal locomotor generator in order to change, for example, the direction of gait. For most other rhythmic elementary motor behavior, such as hopping or swimming, CPGs have also been assumed to exist [93].

3.2.3 Postural control

Posture can be seen as a body position that can be maintained for a relatively long time. It is characterized by a definite set of joint angles [95]. In the past, the maintenance of these

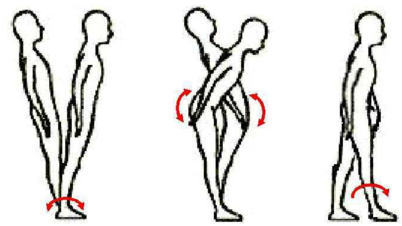


Figure 5: Ankle, hip and step forward postural strategies

joint angles has been explained by the combined action of reflex mechanisms controlled at the lowest levels of the CNS. But postural control is too complex and context-dependent to rely only on reflexes. All the CNS levels are more likely to be involved in postural control. A **postural response** or **postural adjustment** corresponds to muscle activations (or any elements of movement) which maintain body alignments despite disturbances, this is achieved via two main essentials: **reactive and proactive** mechanisms.

3.2.3.1 Reactive mechanisms

Reactive responses occur after an external unexpected disturbances (feedback control). They include **voluntary** movements, muscle **passive stiffness** properties as well as stretch **reflex** loops. Sensory inputs provide information about the nature of the balance disturbance and are also used to trigger appropriate **automatic** postural responses (§.3.2.2). These rapid responses are evoked as soon as there is a disturbance applied to a body segment that tends to cause disequilibrium or changes in postural orientation. Small and slow disturbances translating the CoM in the anteroposterior direction are compensated in most people by swaying the CoM back as a flexible inverted pendulum mainly about the ankles. This stereotyped pattern of muscle activation is known as **ankle strategy** (fig.5). When responding to larger or faster displacements, an action occurs at the hip resulting in active trunk rotation, this response is known as **hip strategy** (fig.5). Subjects may respond with a third strategy, **stepping**, for very large and/or fast perturbations, or when the goal of maintaining a vertical trunk orientation predominates [146] (fig.5).

3.2.3.2 Proactive mechanisms

Proactive mechanisms are elicited when predictable disturbances occur. *1) External predictable disturbances* are often detected by the visual system: informations about environment conditions and changes are constantly received trough eyes and interpreted in the light of experience for its impact on stability [107]. The induced adjustments to avoid perceived obstacles or modify step parameters and increase alertness in potentially hazardous situations such as slippery surfaces. These adjustments prevent the need to recover from the stronger forces that would be imposed by a stumble, slip or trip. **Predictive control** evaluates the external environment by considering the forces acting on the body; it maintains intersegmental stability within the body and between the body and the support surface. It is dependent upon an accurate internal representation of the body and a learned awareness of how any movement or muscle action will alter these relationships [159]. *2) Internal disturbances* induced by voluntary movements are anticipated by the CNS, which produces changes int he background activity of postural muscles: **anticipated postural adjustments (APA)** which are elaborated in a feedforward manner, compensating at least partially for the upcoming perturbation by shifting the CoM in the direction opposite to the perturbation [31]. The simple fact of reaching out to grasp an object can destabilize balance unless precise compensatory action is initiated before the arm is extended. Proactive mechanisms precede and accompany focal movements in order to offset any destabilizing effects of the voluntary movement in a feedforward manner. Through learning an adaptation, the nervous system anticipates the mechanical effects of a voluntary movement and adjusts the amplitude and timing of the accompanying postural component in order to minimize the disturbance to balance. These patterns of movement activity commence prior to voluntary or focal movements: during a arm raising in a standing position, the leg muscles involved in postural control are activated some 50-100ms prior to the prime mover activation [126]. The type and magnitude of APA are determined by the direction and speed of focal movement. The initial response is not based on sensory input but rather on what experience has taught will be the amount and direction of destabilization produced by the focal movement. Reactive adjustments also act to reinforce the anticipatory postural adjustments; they utilize somatosensory and kinesthetic input to guide the extent and the type of their actions, compensating for inadequacies in APA.

The capacity of central processing region is not infinite; therefore performance is reduced in secondary tasks. Balance control although performed at an unconscious level is not an automatic process. The level of attention required to maintain postural control in a challenging position increases from sitting to walking. The amount of information processing required depends on the complexity of the environment and whether it changes throughout the activity. Most environments comprise both fixed and varying elements. Many activities depend on the environment for their performance. There are tasks in which timing is directly linked to the environment: catching a ball, stepping onto an escalator. The timing constraint requires more complex calculations and predictions and further increases the central processing load. Like environment, complex tasks require more information processing than simple ones. Studies of quiet stance have suggested **separate postural control strategies for anteroposterior and mediolateral equilibrium** [84].
Small and slow postural sway during quiet stance should also be part of the postural control and might be important to provide updated and appropriate sensory information helpful to standing balance [84].

3.3 Optimizing the postural tasks

3.3.1 Reducing of the number of variables to control

Postural regulation, in particular during human locomotion, is a complex skill that raises the problem of the many degrees of freedom (DoF) to be controlled [23]. The first attempt of the CNS is to reduce the number of DoF to be controlled simultaneously, in particular while walking [136]. This is obtained by establishing **close relationships between the various angular movements involved**. Thus, the central nervous system presumably solves the problem of high dimensionality by generating a few fundamental signals, which control the major muscle groups in both legs [162]. The reduction of the number of DoF to be controlled simultaneously during movement may be ensured by different means, including stable individual sensory-motor typologies and the corresponding strategies of segmental posture [110, 111, 112]. Current studies are attempting to underline the controlled variables corresponding to different tasks [189]. **CoM is generally considered to be within these controlled variables** [217]. The computational problem of motor planning arises from a fundamental property of the motor system: the reduction in the degrees of freedom that occurs during the transition from neural commands through muscle activation to movement dynamics.

Since execution of voluntary movements is closely linked with the control of posture, it has been proposed that the desired movement (focal component) and the other one which is related to the maintenance of posture (postural component) [22, 23, 126]. The coordination between these two components has been described through the concept of **postural synergies** [23, 5, 201] which correspond to combinations of motor commands to a number of joints leading to a desired common goal such as keeping the CoM projection over the support base.

3.3.2 Building up classified repertories

Reactivity is also linked to the brain ability to build up a directory of postural reactions [105, 15]. There is a continuum of **strategies** whereby the standing human can maintain balance despite disturbances. The ankle and hip strategies, presented before, constituted different ways of reaching the same goal, i.e. maintaining the CoM projection position with respect to the feet. A strategy is implemented by a pattern of muscle activation (synergy) which depends mainly on the body support at the time of the disturbance. There is probably a directory of **synergies** providing stable muscle pattern [157] and this set may be used by sensory inputs associated with voluntary movement. This organization would also reduce the number of degrees of freedom and simplify the problem of motor control in the domain of postural adjustment in line [23]. It has been suggested that the **CNS does not plan and control strategies by determining each simple variable** such as joint angular displacements or velocity, but by using a topological, or map-like, **internal representation** of movement in which a whole continuum of possible, equivalent strategies could achieve a particular goal [1, 65].

3.3.3 Postural body scheme

An important feature in the control of human movements is the existence of anticipatory postural adjustments (APA). They result in the existence of an internal representation of movement execution and surroundings. The brain is thus functioning as an anticipating machine able to built up an internal model of its most predictable environment and to use it for driving action and predicting the consequences of the descending motor command [163, 25].
A specific internal representation for posture, that neuroscientists call the **postural body scheme**, has been proposed by Clément et al. [47] and Lestienne and Gurfinkel [130], on the basis of experiments carried out during space flights under microgravity. This internal model of postural orientation includes the representation of body configuration and dynamics, the perception of the borders between the body and extra personal space, the knowledge of sensory dynamics and expected sensory inputs and the formation of task-dependent stationary reference systems [96]. Taking into account the biomechanical properties of the head, trunk and limbs, this internal representation allows in particular building up a directory of APA. The vast directory of postural representations, and their relationship to environmental and behavioral contexts, can best be understood by supposing that the nervous system integrates all available sensory information into a common "orientation interpretation center" based on an internal model of the body [127].
The concept of the body scheme is not specific to posture, but there is a specific internal body representation for posture [47, 130]. The very stable body representation may be partly genetically determined and partly acquired through learning. It includes a representation of the verticality based on the labyrinthine, proprioceptive and visual inputs and on the perception of the longitudinal trunk axis [151].
Internal models can be segregated into two categories, namely **forward models** and **inverse models**. A forward model predicts the behavior of the motor system in response to a command and allows the CNS to estimate the current and future state of the effectors immediately and without peripheral information. The idea behind this concept is that the central nervous system can progressively "learn" to estimate the behavior of the motor plan in response to a given command. By integrating information that is related to initial movement conditions, such as motor outflow and sensory inflow, the probable position and velocity of the effector can be determined and even predicted (note: this indirect inversion is a technique also used in robotics). When a forward model is used to feed an internal feedback loop, control performance is improved significantly inasmuch as large delays that are associated with sensory feedback loops can be avoided. When required to reach a target, a subject first elaborates a motor plan, based on the initial movement conditions (i.e. the respective locations of the hand and target). During the realization of the movement, a forward model of the dynamics of the arm is generated. In its simplest version, this model receives as input a copy of the motor outflow. Based on this information, the end-point of the movement can be predicted and continuously compared to the target location. Forward models are interesting in the context of feedback control systems. For instance, a forward model can produce an estimate of the movement end-point location as output, which can be compared to the target location. In the case of a discrepancy, a corrective command can be

generated. This forward model integrates the sensory inflow and motor outflow to evaluate the consequences of the motor commands sent to a limb. The probable position and velocity of an effector should then be estimated with negligible delays and even predicted in advance, thus making feedback strategies possible for fast reaching movements for instance. Inverse models take into account the inertial and viscous properties of a limb to estimate the motor command that will produce the desired displacement.

3.3.4 Minimization of the energy consumption

An individual moves in such a way he reduces his total effort to a minimum, consistent with the constraints [161, 185]. Many studies have been devoted to metabolic energy cost during locomotion in untrained healthy humans, athletes, as well as in patients with various motor diseases [206, 219]. These previous studies show the particular importance of energetic aspects of movement, that concern both improving motor performance and minimizing fatigue. Energy cost may be defined as the work done at each step to lift the CoM of the body, to accelerate it forward, and to increase the mechanical energy (sum of both gravitational potential and kinetic energies) [42]. It can be estimated by measuring variations in respiratory, heart rate, body temperature, pulmonary ventilation and oxygen consumption [2]. Generating horizontal propulsive forces constitutes nearly half of the metabolic cost of normal walking [90]. Minimizing this energy consumption per unit distance is an important goal of locomotor development [42, 52]. It appears that it can be saved in many different ways [3]: by adjusting the maximum shortening speeds of muscles for a given task, adjusting the moments exerted by the muscles at different joints to keep the ground force in line with the leg so that muscles do not work against each other, keeping the leg joints as straight as possible to minimize muscle force and work requirements... Tendon and other springs can be used to store elastic strain energy and to return it by elastic recoil [4, 122, 172, 180]. An important energy-saving mechanism in walking is the alternate transfer between gravitational-potential energy and kinetic energy within each stride (as takes place in a pendulum) [43]. The transformation of both energies during each stride is estimated to comprise 50% to 70% of the energy demand in walking at moderate speeds [184]. The control of inter-segmental kinematics phase may be used for limiting the overall energy expenditure with increasing walking speed [128]. At each speed is used the stride length that minimizes energy costs. Step width may also be optimized to minimize the mechanical work required for redirecting the center of mass velocity during the transition between single stance phases [62].
It should be noted that there is no standardization in the efficiency of the strategies adopted by human walkers to minimize energy expenditure [27]. This shows the importance of individual history, training or ageing [145, 137], which may give rise to various levels of efficiency and ability to save energy.
Other aspects than normal walking at steady speed on level ground may also require adaptation for energy saving, such as determining the transition speed between walking and running, corresponding to the speed at which walking becomes less economical than running [147, 54, 34, 178], or such as walking on a moving support [102] or on surfaces of different stiffnesses [220, 129, 123] or slopes [149, 150] or carrying loads [44].

3.3.5 Minimizing the consequences of signal-dependent noise

Despite the existence of noise and variability in the motor system the performed movements are efficient [97]. Joint torques during voluntary activation are affected by various factors such as the accuracy of the descending motor commands, the number and characteristics of muscles which cross the joint. It has been proposed that movements cannot be both fast and accurate: there is a speed-accuracy trade-off [76], and that as the force produced increases, the standard deviation of the force increases in a linear fashion [187]. Reducing the consequences of signal-dependent noise is therefore a fundamental strategy in human motor control [99].

The presence of noise in the motor system induces inaccuracy. Different trajectories from the set of all possible trajectories that can achieve a task may have different error distributions. Under the possible solutions, the motor system picks the trajectory that minimizes the consequences of signal dependent noise in the relevant task dimension. Use of these is also able to account for the stereotyped trajectories observed in obstacle avoidance movements [97]. At the force level, muscle activation patterns are redundant, that is more efficient than one muscle activation pattern can be used to achieve the same joint torque. Between two solutions of muscles activation, the motor system is likely to choose the less noisy [97].

3.4 Locomotor development and training : why and how?

Human bipedal locomotion is aimed at displacing the whole body while ensuring its balance. It is a complex task, consisting in a compromise between the forward propulsion of the body, which is a highly destabilizing force, and the need to maintain the lateral and vertical stability of the body [15, 33].

Acquisition of equilibrium during human development is a source of information of high importance to understand the CNS. **Acquiring a sensory-motor ability during childhood has a similar progression to the one of learning a new ability in adults**. At the beginning, movements are dominated by an uncontrolled dynamics which leads to a weak postural stabilization. Then individuals learn to suppress the effects of passive dynamics by a muscular control. They learn to use the dynamics, inherent to movement, in order to reduce the amount of active muscle control and metabolic energy necessary to achieve the action [23, 160, 188, 194]. According to Vaughan [199], when a young child takes its first few halting steps, his or her biomechanical strategy is to minimize the risk of falling. Actually, during the crucial period of learning of independent walking, and for the subsequent few years, the child's CNS will mature in parallel with musculoskeletal growth. Subsequently, the various components of human locomotor behaviors which have to be acquired during ontogenesis take a long time to be trained before being ideally achieved. This long period of development is presumably due not only to the progressive growth of the human biomechanical system and the maturation of the central nervous system, but also to the building up of motor strategies that overcome purely biomechanical constraints of oscillating systems and are aimed at **smoothing movements and saving energy expenditure**. Indeed, the descending organization of the segmental movement all along the spine during adult locomotion cannot be purely due to biomechanics, but rather to anticipate locomotor disequilibrium. Similarly, the angular head stabilization in space while walking, on which the descending (anticipatory) organization of equilibrium control seems to be based, does not obey simple biomechanical laws, but is aimed at constituting an appropriately built spatial frame of reference to execute corrections of imbalance thanks to visual and vestibular error signals [16, 15]. Another feature that cannot be explained simply by biomechanical reasons is the anticipatory control of the vertical trajectory of the CoM (vertical equilibrium) at heel contact. All these strategies cannot be simply innate, due to interindividual differences in size and weight and their variations with age, which would not be the case in robots. They constitute in adults a **redundant directory of motor strategies**, from the simplest to the most sophisticated one, allowing adaptation to changes in external context or in the subject's abilities due to normal aging or pathological deficits. In the last case, a regression from the most elaborate and efficient strategies to the simplest ones resembling to those adopted by young children can often be observed [15, 79].

In terms of equilibrium and strategies of segmental stabilization, several steps can be distinguished in the development of human locomotion [15]. At the very beginning of the autonomous locomotion, toddlers use to walk with their feet largely apart, a simple strategy which enlarges the supporting surface and facilitate equilibrium control. It is only since the age of three years that they become able to walk on a narrow surface, namely with their feet in front one of another [15]. As regards the angular stabilization of body segments, the pelvis stabilization in space appears from the first week of autonomous walking and clearly precedes those of the shoulder (two months after the beginning of autonomous walking) and of the head, which does not efficiently appear before 4 years during ground locomotion [16, 17]. The early pelvis stabilization in space is presumably aimed at minimizing the lateral movements of the center of mass and avoiding fall of the hip towards the swing leg, and this strategy seems to be a prerequisite for autonomous walking in toddlers. At that time, locomotor balance control is organized temporally in an ascending fashion, from hip to head. Moreover, an anticipatory activity at the hip level with respect to the feet movements suggests a hip-centered organization : ascending (bottom-up) from hip to head and descending (top-down) from hip to foot [16, 17]. From the age of 7 onwards, children become able to progressively adopt and master the strategy of head stabilization in space around the three main axes in response to an increase in the level of dynamic equilibrium difficulty such as walking over a straight line or on a narrow beam [16]. Lastly in adulthood, the head stabilization in space is commonly adopted but specifically involves the roll component, presumably for economy and to protect against visual instability and subsequent visual blurring due to the eye's limited ability to roll to compensating for head oscillations [91]. This strategy is then systematically associated with a pure **descending organization of the spine movements** [16, 195, 173, 156].

4 Conclusion

Our attempt in this paper was to propose a synthesis of the problem of controlling bipedal locomotion in humans and robots.
A main difference between biped robots and human is the redundancy. Regarding body structure and actuation, robots are usually provided with the minimum number of elements which are theoretically required to ensure standing and walking. Humans are highly more complex than any existing robot: three hundred degrees of freedom insure redundancy in the choice of possible postures for a same task. Basic locomotion can be achieved through the fifteen degrees of freedom, which are, at best, available in biped robots [186]. The available margins to realize one task and to execute several movements at the same time are therefore limited. But redundancy is also a property of human sensors: information encoded by each sensor is unique, and each class of receptor operates optimally within a specific range of frequency and amplitude of body motion, allowing for solving ambiguities [140]. The anticipation ability is highly linked to the sensors properties of measuring rapid variations (derivatives).
If brain cannot be directly compared to a computer, they both play the role of a real-time controller. Some concepts like hierarchical and decentralized architectures, multi-task, multi-clock, parallelism, multi-sensor fusion can be common ones to exploit in both neuroscience and robotics.
Human are subjected to constraints similar to those of machines: transmission delays, unperfect measurements, computation power limitation... If delayed or incomplete sensory information is detrimental for most robotic systems, animal motor behavior can be surprisingly accurate during similar conditions.
Considering the complexity of the body and the time delays imposed to human CNS, it is obvious that the brain makes some assumptions on the system state using simplified model and concentrating on the control of a reduced number of variables [189]. Researches in the field of dynamic modeling of mechanical systems submitted to contacts and impacts allow to simulate more and more precisely the robots. The complexity of these models is very time consuming in a real-time resolution objective. Embedded models have to allow a good estimation of the reality taking into account only the essential aspects oriented to the goal, in order to limit the computation delays.
Robotics provides a theoretical framework to formalize the problem of biped control. Concepts like postural control can be expressed into a mathematical definition (section 2) allowing therefore to work in a precise context instead of an intuitive one.
We believe that bringing together robotics and neuroscience around the problematic of biped system control could be of benefit for both disciplines.

References

[1] J.H. Abbs and K.J. Cole. Neural mechanisms of motor equivalence and goal achievement. In *Higher Brain Functions. Recent Explorations of the Brains's Emergent Properties*, pages 15–43. Edited by S.P. Wise. New York: John Wiley & Sons, 1987.

[2] M.M. Abitbol. Effect of posture and locomotion on energy expenditure. *Am. J. Phys. Anthropol.*, 77:191–199, 1988.

[3] R.M. Alexander. Energy-saving mechanisms in walking and running. *J.Exp.Biol.*, 160:55–69, 1991.

[4] R.M. Alexander and H.C. Bennet-Clark. Storage of elastic strain energy in muscle and other tissues. *Nature*, 265:114–117, 1977.

[5] A. Alexandrov, R. Aurenty, J. Massion, S. Mesure, and F. Viallet. Axial synergies in parkinsonian patients during voluntary trunk bending. *Gait Posture*, 8(2):124–135, 1998.

[6] P. Allard and J.P. Blanchi. *Analyse du mouvement humain par la biomécanique.* Décarie Éditeur, Québec, Canada, 1996.

[7] F. Allgower, T.A. Badgwell, J.S. Qion, J.B. Rawlings, and S.J. Wright. Nonlinear predictive control and moving horizon estimation. an introduction overview. In *Proceedings of the European Control Conference (ECC)*, pages 392–449, Karlsruhe, Germany, September 1999.

[8] B. Amblard, C. Assaiante, J. Crémieux, and Marchand. *From posture to gait: Which sensory input for which function?* Edited by T. Brandt, W. Paulus, W. Bles, M. Dieterich, S. Krafczyk, A. Straube. Stuttgart, New York: Georg Thieme Verlag, 1990.

[9] B. Amblard, J. Crémieux, A.R. Marchand, and A. Carblanc. Lateral orientation and stabilization of human stance: static versus dynamic visual cues. *Experimental Brain Research*, 61:21–37, 1985.

[10] B. Amblard, M. Vaugoyeau, C. Schmitz, and C. Assaiante. Functional approach to strategies of segmental posture during stance and movement: Development, variability and disorders. -, In preparation.

[11] D. Anastasopoulos and T. Mergner. Canal-neck interaction in vestibular nuclear neurons of the cat. *Experimental Brain Research*, 46(2):269–28, 1982.

[12] F. Asano, Z. Luo, and M. Yamakita. Some extensions of passive walking formula to active biped robots. In *IEEE International Conference on Robotics & Automation*, pages 3797–3802, New Orleans, USA, April 2004.

[13] B.M. Ashby and J.H. Heegaard. Role of arm motion in the standing long jump. *J.Biomech.*, 35(12):1631–1637, 2002.

[14] `http://world.honda.com/ASIMO/`.

[15] C. Assaiante and B. Amblard. An ontogenetic model for the sensorimotor organization of balance control in humans. *Human Movement Science*, 14:13–43, 1995.

[16] C. Assaiante, B. Thomachot, and R. Aurenty. Hip stabilization and lateral balance control in toddlers during the first four months of autonomous walking. *NeuroReport*, 4(7):875–878, 1993.

[17] C. Assaiante, B. Thomachot, R. Aurenty, and B. Amblard. Organization of lateral balance control in toddlers during the first year of autonomous walking. *J. of Motor Behavior*, 30(2):114–129, 1998.

[18] J.P. Aubin. *Viability Theory.* Birkhäuser, 1991.

[19] C. Azevedo, N. Andreff, and S. Arias. Bipedal walking from gait design to experimental analysis. *Mechatronics*, 14/6:639–665, 2004.

[20] C. Azevedo, P. Poignet, and B. Espiau. Artificial locomotion control: from human to robots. *Robotics and Autonomous Systems (RAS) Elsevier*, 47/4:203–223, 2004.

[21] C. Bard, J. Paillard, Y. Lajoie, M. Fleury, N. Teasdale, R. Forget, and Y. Lammare. Role of afferent information in the timing of motor commands, a comparative study with a deafferented patient. *Neuropsychologia*, 30(2):201–206, 1992.

[22] V.Y. Belinkiy, V.S. Gurfinkel, and Y.L. Patslev. Elements of control of voluntary movements. *Biophysics*, 12:154–161, 1967.

[23] N.A. Bernstein. *The Coordination and Regulation of Movement.* NewYork: Pergamon Press, 1967.

[24] A. Berthoz. *Reference frames for the perception and control of movement.* Paillard J (Ed.) Brain and Space. Oxford University Press, Oxford, 1991.

[25] A. Berthoz. *Le sens du mouvement.* Edited by Odile jacob, 1997.

[26] A. Berthoz and T. Pozzo. *Intermittent head stabilization during postural and locomotory tasks in humans.* Amblard B, Berthoz A, Clarac F (eds.) Posture and gait: Development, adaptation and modulation. Elsevier, Amsterdam, 1988.

[27] L. Bianchi, D. Angelini, and F. Lacquaniti. Individual characteristics of human walking mechanics. *Pflugers Arch.*, 436:343–356, 1998.

[28] `http://www.inrialpes.fr/bipop/bip/welcome.html#english`.

[29] R. Bischoff. *System Reliability and Safety Concepts of the Humanoid Service Robot HERMES*, volume I-2. Proc. IARP/IEEE-RAS Joint Workshop on Technical Challenge for Dependable Robots in Human Environments, May 2001.

[30] J. Blouin, C. Bard, N. Teasdale, J. Paillard, M. Fleury, R. Forget, and Y. Lamarre. Reference systems for coding spatial information in normal subjects and a deafferented patient. *Experimental Brain Research*, 93(2):324–331, 1993.

[31] S. Bouisset and M. Zattara. iomechanical study of the programming of anticipatory postural adjustments associated with voluntary movement. *B. J Biomech*, 20:735–742, 1987.

[32] J.-M. Bourgeot, N. Cislo, and B. Espiau. Path-planning and tracking in a 3D complex environment for an anthropomorphic biped robot. In *Proc. of the 2002 IEEE Intl. Conf. on Intelligent Robots and Systems*, volume 3, pages 2509–2514, EPFL, Lausanne, Suisse, October 2002.

[33] Y. Brenière, B. Bril, and R. Fontaine. Analysis of the transition from upright stance to steady state locomotion in children with under 200 days of autonomous walking. *Journal of Motor Behavior*, 21(1):20–37, 1989.

[34] J. Brisswalter and D. Mottet. Energy cost and stride duration variability at preferred transition gait speed between walking and running. *Can. J. Appl. Physiol*, 21:471–480, 1996.

[35] J.D. Brooke, W.E. McIlroy, D.F. Collins, and J.E. Misiaszek. Mechanisms within the human spinal cord suppress fast reflexes to control the movement of the legs. *Brain Res.*, 679:255–260, 1995.

[36] V.B. Brooks. *The neural basis of motor control.* Oxford, University Press, Oxford, 1986.

[37] B. Espiau C. Samson, M. Le Borgne. *Robot Control: the Task Function Approach.* Oxford University Press, 1991.

[38] C. Capaday. The special nature of human walking and its neural control. *Trends Neurosci.*, 25:370–376, 2002.

[39] C. Capaday, B. Lavoie, H. Barbeau, C. Schneider, and M. Bonnard. Studies on the corticospinal control of human walking: I. responses to focal transcranial magnetic stimulation of the motor cortex. *J. Neurophysiol.*, 81:129–139, 1999.

[40] A. Cappozzo. Gait analysis methodology. *Human Movement Sience*, 3:27–50, 1984.

[41] D.R. Carrier, N.C. Heglund, and K.E. Earls. Variable gearing during locomotion in the human musculoskeletal system. *Science*, 265:651–653, 1994.

[42] G.A. Cavagna, P. Franzetti, and T. Fuchimoto. The mechanics of walking in children. *J. Physiol*, 343:323–339, 1983.

[43] G.A. Cavagna, H. Thys, and A. Zamboni. The sources of external work in level walking and running. *J. Physiol*, 262:639–657, 1976.

[44] G.A. Cavagna, P.A. Willems, M.A. Legramandi, and N.C. Heglund. Pendular energy transduction within the step in human walking. *J. Exp. Biol.*, 205:3413–3422, 2002.

[45] S. Chessé and G. Bessonnet. *Optimal Dynamics of Constrained Multibody Systems. Application to Bipedal Walking System Synthesis.* IEEE International Conference on Robotics & Automation, 2001.

[46] C. Chevallereau, J.W. Grizzle, and C.H. Moog. Nonlinear control of mechanical systems with one degree of actuation. In *IEEE International Conference on Robotics & Automation*, New Orleans, USA, April 2004.

[47] G. Clément, V.S. Gurfinkel, F. Lestienne, M.I. Lipshits, and K.E. Popov. Adaptation of postural control to weightlessness. *Experimental Brain Research*, 57:61–72, 1984.

[48] S.H. Collins, M. Wisse, and A. Ruina. A three-dimensional passive dynamic walking robot with two legs and knees. *The International Journal of Robotics Research*, 20(7):607–615, 2001.

[49] P. Crenna and C. Frigo. Evidence of phase-dependent nociceptive reflexes during locomotion in man. *Exp Neurol*, 85(2):336–345, 1984.

[50] P. Crenna, C. Frigo, J. Massion, and A. Pedotti. Forward and backward axial synergies in man. *Exp. Brain Res.*, 65:538–548, 1987.

[51] J. Crosbie, R. Vachalathiti, and R. Smith. Patterns of spinal motion during walking. *Gait and Posture*, 5:6–12, 1997.

[52] D. DeJaeger, P.A. Willems, and N.C. Heglund. The energy cost of walking in children. *Pflugers Arch.*, 441:538–543, 2001.

[53] M. Desmurget and S. Grafton. Forward modelling allows feedback control for fast reaching movements. *Trends in Cognitive Science*, 4(11):423–431, 2000.

[54] F.J. Diedrich and W.H. Warren Jr. Why change gaits? dynamics of the walk-run transition. *J.Exp.Psychol.Hum.Percept.Perform.*, 21:183–202, 1995.

[55] V. Dietz. Interaction between central programs and afferent input in the control of posture and locomotion. *Journal of Biomechanics*, 29(7):841–844, 1996.

[56] V. Dietz. Do human bipeds use quadrupedal coordination? *Trends Neurosci.*, 25(9):462–467, 2002.

[57] V. Dietz. Spinal cord pattern generators for locomotion. *Clin. Neurophysiol.*, 114:1379–1389, 2003.

[58] V. Dietz, K. Fouad, and C.M. Bastiaanse. Neuronal coordination of arm and leg movements during human locomotion. *Eur. J. Neurosci.*, 14(11):1906–1914, 2001.

[59] M.R. Dimitrijevic, Y. Gerasimenko, and M.M. Pinter. Evidence for a spinal central pattern generator in humans. *Ann. N. Y. Acad. Sci.*, 860:360–376, 1998.

[60] B. Dobkin. Recovery of locomotor control. *Neurologist*, 2:239–249, 1996.

[61] B. Dobkin, A. Firestine, M. West, K. Saremi, and R. Woods. Ankle dorsiflexion as an fmri paradigm to assay motor control for walking during rehabilitation. *NeuroImage*, 23:370–381, 2004.

[62] J.M. Donelan, R. Kram, and A.D. Kuo. Mechanical and metabolic determinants of the preferred step width in human walking. *Proc.R.Soc.Lond B Biol.Sci.*, 268:1985–1992, 2001.

[63] S.F. Donker, P.J. Beek, R.C. Wagenaar, and T. Mulder. Coordination between arm and leg movements during locomotion. *J. Mot. Behav.*, 33(1):86–102, 2001.

[64] S.F. Donker, T. Mulder, B. Nienhuis, and J. Duysens. Adaptations in arm movements for added mass to wrist or ankle during walking. *Exp. Brain Res.*, 146(1):26–31, 2002.

[65] J. Droulez and A. Berthoz. *Servo-controlled (conservative) versus topological (projective) mode of sensory motor control.* Edited by T. Brandt. Amsterdam: Elsevier Science Publishers, 1986.

[66] D.C. Dunbar. Locomotor behavior of rhesus macaques (macaca mulatta) on cayo santiago. *P.R.Health Sci.J.*, 8:79–85, 1989.

[67] J. Duysens, F. Clarac, and H. Cruse. Load-regulating mechanisms in gait and posture: Comparative aspects. *Physiological Reviews*, 80-1:83–133, 2000.

[68] J. Duysens, A.A.M. Tax, S. Nawijn, W. Berger, T. Prokop, and E. Altenmuller. Gating of sensation and evoked potentials following foot stimulation during human gait. *Experimental Brain Research*, 105(3):423–431, 1995.

[69] J. Duysens and H.W.A.A. Van de Crommert. Neural control of locomotion; the central pattern generator from cats to humans. *Gait and Posture*, 7:131–141, 1998.

[70] J. Duysens, H.W.A.A. Van de Crommert, B.C.M. Smits-Engelsmanc, and F.C.T. Van der Helm. A walking robot called human: lessons to be learned from neural control of locomotion. *Journal of Biomechanics*, 35:447–453, 2002.

[71] J.C. Eccles. *The understanding of the brain.* McGraw-Hill, New York, 1977.

[72] G. Endo, J. Morimoto, J. Nakanishi, and G. Cheng. An empirical exploration of a neural control oscillator for biped locomotion control. In *IEEE International Conference on Robotics & Automation*, pages 3036–3042, New Orleans, USA, April 2004.

[73] J.J. Eng, D.A. Winter, C.D. MacKinnon, A.E. Patla, and N. Ishida. *Role of the torque stabiliser in postural control during rapid voluntary arm movements.* Woollacott M. and Horak F. (Eds), oregon: University of Oregon, 1992.

[74] B. Espiau and F. Génot. *Les robots marcheurs bipèdes.* La robotique mobile - Hermes, 2002.

[75] B. Espiau and P. Sardain. The anthropomorphic biped robot bip2000. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 3997–4002, San Francisco, USA, April 2000.

[76] P.M. Fitts. The information capacity of the human motor system in controlling the amplitude of movement. *J. Exp. Psychol.*, 47(6):381–91, 1954.

[77] J.R. Flanagan and A.M. Wing. The role of internal models in motion planning and control: evidence from grip force adjustments during movements of hand-held loads. *J. Neurosci.*, 17(4):1519–1528, 1997.

[78] H. Forssberg. Ontogeny of human locomotor control. i. infant stepping, supported locomotion and transition to independent locomotion. *Exp Brain Res*, 57(3):480–493, 1985.

[79] H. Forssberg, B. Johnels, and G. Steg. Is parkinsonian gait caused by a regression to an immature walking pattern? *Adv Neurol*, 40:375–379, 1984.

[80] Y. Fujimoto. Trajectory generation of biped running robot with mimimum energy consumption. In *IEEE International Conference on Robotics & Automation*, pages 3803–3808, New Orleans, USA, April 2004.

[81] H. Fukuyama, Y. Ouchi, S. Matsuzaki, Y. Nagahama, H. Yamauchi, M. Ogawa, and et al. Brain functional activity during gait in normal subjects: a spect study. *Neurosci. Lett.*, 228:183–186, 1997.

[82] J.R. Gage. An overview of normal walking. In *American Academy of Orthopaedic Surgeons, Instructional Course Lectures*, volume XXXVIII, 1990.

[83] Y. Gahéry and J. Massion. Coordination between posture and movement. *TINS*, 4:199–202, 1981.

[84] P. Gatev, T. Thomas, S.and Kepple, and M. Hallett. Feedforward ankle strategy of balance during quiet stance in adults. *Journal of Physiology (London)*, 514:915–928, 1999.

[85] L.A. Gilchrist and D.A. Winter. A two-part, viscoelastic foot model for use in gait simulations. *Journal of Biomechanics*, 29(6):795–798, 1996.

[86] P. Glardon, R. Boulic, and D. Thalmann. Pca-based walking engine using motion capture data. In *Computer Graphics International*, Crete, Greece, june 2004.

[87] P. Gorce and O. Vanel. Behaviour synthesis of the erect stance for a biped control. *Journal of Intelligent and Robotic Systems*, pages 127–145, 1997.

[88] C.R. Gordon, W.A. Fletcher, J.G. Melvill, and E.W. Block. Adaptive plasticity in the control of locomotor trajectory. *Experimental Brain Research*, 102:540–545, 1995.

[89] A. Goswami, B. Thuilot, and B. Espiau. A study of the passive gait of a compass-like biped robot: Symmetry and chaos. *The International Journal of Robotics Research*, 17(12):1282–1301, 1998.

[90] J.S. Gottschall and R. Kram. Energy cost and muscular activity required for propulsion during walking. *J. Appl. Physiol.*, 94(5):1766–1772, 2003.

[91] M.A. Gresty and A.M. Bronstein. Visually controlled spatial stabilisation of the human head: compensation for the eye's limited ability to roll. *Neurosci.Lett.*, 140:63–66, 1992.

[92] M.J. Grey, B. Larsen, and T. Sinkjaer. A task dependent change in the medium latency component of the soleus stretch reflex. *Experimental Brain Research*, 145:316–322, 2000.

[93] S. Grillner. *Interaction between sensory signals and the central networks controlling locomotion in lamprey, dogfish and cat*, volume 45. S. Grillner, P.S.G. Stein, D.G. Stuart, F. Forssberg and R.M. Herman, Editors, Wenner Gren international symposium seriesWenner Gren international symposium series, Macmillan, London, 1986.

[94] G.E. Grossman, R.J. Leigh, L.A. Abel, D.J. Lanska, and S.E. Thurston. Frequency and velocity of rotational head perturbations during locomotion. *Experimental Brain Research*, 70:470–476, 1988.

[95] V.S. Gurfinkel and Y.S. Levick. *Perceptual and automatic aspects of the postural body scheme.* Edited by J. Paillard. Oxford: Oxford University Press, 1991.

[96] V.S. Gurfinkel, Y.S. Levick, B. Popov, N. Smetanin, and V.Y. Shlikov. *Body scheme in the control of postural activity.* Edited by V.S. Gurfinkel, M.E. Ioffe, J. Massion, J.P. Roll. New York: Plenum Press, 1988.

[97] A.F. Hamilton de C. and DM. Wolpert. Controlling the statistics of action: obstacle avoidance. *J. Neurophysiol*, 87:2434–2440, 2002.

[98] E. Hanada and D.C. Kerrigan. Energy consumption during level walking with arm and knee immobilized. *Arch. Phys. Med. Rehabil.*, 82(9):1251–1254, 2001.

[99] C.M. Harris and D.M. Wolpert. Signal-dependent noise determines motor planning. *Nature*, 394(6695):780–784, 1998.

[100] M. Haruno, D.M. Wolpert, and M. Kawato. Mosaic model for sensorimotor learning and control. *Neural Comput*, 13, 2001.

[101] M. Haruno, D.M. Wolpert, and M. Kawato. Hierarchical mosaic for movement generation. *International Congress Series 1250*, pages 575–590, 2003.

[102] R. Heus, A.H. Wertheim, and G. Havenith. Human energy expenditure when walking on a moving platform. *Eur.J.Appl.Physiol Occup.Physiol*, 77:388–394, 1998.

[103] K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka. The development of the honda humanoid robot. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 1321–1326, Leuven, Belgium, May 1998.

[104] F.B. Horak and J.M. MacPherson. *Postural Orientation and Equilibrium.* L.B. Rowell and J.T. Shepherd, 1996.

[105] F.B. Horak and L.M. Nashner. Central programming of postural movements: adaptation to altered support-surface configurations. *J. Physiol. (Lond.)*, 55:1369–1381, 1986.

[106] Y. Hurmuzlu, F. Génot, and B. Brogliato. Modelling, stability and control of biped robots - a general framework. Technical Report 4290, INRIA Research Report, 2001.

[107] F.E. Huxham, P.A. Goldie, and A.E. Patla. Theoretical considerations in balance assessment. *Australian journal of Physiotherapy*, 47:89–100, 2001.

[108] H. Imamizu, T. Kuroda, S. Miyauchi, T. Yoshioka, and M. Kawato. Modular organization of internal models of tools in the human cerebellum. *Proc.Natl.Acad.Sci.U.S.A*, 100:5461–5466, 2003.

[109] M.E. Ioffé and A.E. Andreyev. Inter-extremities coordination in local motor conditioned reactions of dogs. *Zh. Vyssh. Nervn. Deyat. Pavlova*, 19:557–465, 1969.

[110] B. Isableu, T. Ohlmann, J. Crémieux, and B. Amblard. Selection of spatial frame of reference and postural control variability. *Experimental Brain Research*, 114:584–589, 1997.

[111] B. Isableu, T. Ohlmann, J. Crémieux, and B. Amblard. How dynamic visual field dependence-independence interacts with the visual contribution to postural control. *Hum mov science*, 17:367–391, 1998.

[112] B. Isableu, T. Ohlmann, J. Crémieux, and B. Amblard. Differential approach to strategies of segmental stabilisation in postural control. *Experimental Brain Research*, 150:208–221, 2003.

[113] K. M. Jackson. Why the upper limbs move during human walking. *J. Theor. Biol.*, 105(2):311–315, 1983.

[114] M. Jeannerod. *The neural and behavioral organization of goal-directed movements.* Clarendon press, 1988.

[115] http://www.amm.mw.tu-muenchen.de/Forschung/ZWEIBEINER/johnnie_e.html.

[116] S. Kajita, K. Yokoi, M. Saigo, and K. Tanie. Balancing a humanoid robot using backdrive concerned torque control and direct angular momentum feedback. In *IEEE International Conference on Robotics & Automation*, Seoul, Korea, May 2001.

[117] C. Kambhampati and S. Rajasekharan. A human motor control perspective to multiple manipulator modelling. *Biol Cybern.*, 89(4):254–263, 2003.

[118] M. Kawato. Internal models for motote control and trajectory planning. In *Current Position in Neurobiology*, volume 9(6), pages 718–727, 1999.

[119] M. Kawato, K. Furukawa, and R. Suzuki. A hierarchical neural-network model for control and learning of voluntary movement. *Biol. Cybern*, 57:169–185, 1987.

[120] P. Kejnonen. *Body movements during postural stabilization.* PhD thesis, University of Oulu, 2002.

[121] R.F. Ker. The time-dependent mechanical properties of the human heel pad in the context of locomotion. *Journal of Experimental Biology*, 199(7):1501–1508, 1996.

[122] R.F. Ker, M.B. Bennett, S.R. Bibby, R.C. Kester, and R.M. Alexander. The spring in the arch of the human foot. *Nature*, 325:147–149, 1987.

[123] A.E. Kerdok, A.A. Biewener, T.A. McMahon, P.G. Weyand, and H.M. Herr. Energetics and mechanics of human running on surfaces of different stiffnesses. *J. Appl. Physiol*, 92:469–478, 2002.

[124] J. Kim and J. Oh. Walking control of the humanoid control platform khr-1 based on torque feedback control. In *IEEE International Conference on Robotics & Automation*, pages 623–628, New Orleans, USA, April 2004.

[125] R. Knight and U. Nehmzow. Walking robots - a survey and a research proposal. *Department of Computer Science, University of Essex, Technical Report CSM-375*, October 2002.

[126] V. Krishnamoorthy. *Muscle synergies during standing.* PhD thesis, College of health and Human Development. Pennsylvania State University, 2003.

[127] J.R. Lackner and M. Levine. Changes in apparent body orientation and sensory localization indued by vibration of postural muscles: vibratory myesthetic illusions. *Aviat. Space Environ. Med.*, 50:346–354, 1979.

[128] F. Lacquaniti, Y.P. Ivanenko, and M. Zago. Kinematic control of walking. *Arch. Ital. Biol.*, 140:263–272, 2002.

[129] T.M. Lejeune, P.A. Willems, and N.C. Heglund. Mechanics and energetics of human locomotion on sand. *J. Exp .Biol.*, 201:2071–2080, 1998.

[130] F. Lestienne and V.S. Gurfinkel. Postural control in weightlessness: a dual process underlying adaptation to an unusual environment. *TINS*, 11:359–363, 1988.

[131] Y. Li, W. Wang, R.H. Crompton, and M.M. Gunther. Free vertical moments and transverse forces in human walking and their role in relation to arm-swing. *J. Exp. Biol.*, 204(1):47–58, 200.

[132] S. Lohmeier, K. Löffler, M. Gienger, H. Ulbrich, and F. Pfeiffer. Computer system and control of biped "johnnie". In *IEEE International Conference on Robotics & Automation*, pages 4222–4227, New Orleans, USA, April 2004.

[133] Fabien Lydoire, Philippe Poignet, Christine Azevedo, and Bernard Espiau. Three-dimensional paramaterized gaits for biped walking. In *Proceedings of the 5th International Conference on Climbing and Walking Robots (CLAWAR)*, pages 749–757, Paris, 2002.

[134] M. MacKay-Lyons. Central pattern generation of locomotion: a review of the evidence. *Phys.Ther.*, 82:69–83, 2002.

[135] C.D. Mackinnon and D.A. Winter. Control of whole body balance in the frontal plane during human walking. *Journal of Biomechanics*, 26(6):633–644, 1993.

[136] C.D. Mah, M. Hulliger, R.G. Lee, and I.S. O'Callaghan. Quantitative analysis of human movement synergies: Constructive pattern for gait. *Journal of Motor Behavior*, 26((2)):83–102, 1994.

[137] D. Malatesta, D. Simar, Y. Dauvilliers, R. Candau, F. Borrani, C. Prefaut, and C. Caillaud. Energy cost of walking and gait instability in healthy 65- and 80-yr-olds. *J.Appl.Physiol*, 95:2248–2256, 2003.

[138] D.S. Marigold, A.J. Bethune, and A.E. Patla. Role of the unperturbed limb and arms in the reactive recovery response to an unexpected slip during locomotion. *J. Neurophysiol.*, 89(4):1727–1737, 2003.

[139] D.S. Marigold and A.E. Patla. Strategies for dynamic stability during locomotion on a slippery surface: effects of prior experience and knowledge. *J. Neurophysiol.*, 88(1):339–353, 2002.

[140] J. Massion. Movement, posture and equilibrium: Interaction and coordination. *Progress in Neurobiology*, 38:35–56, 1992.

[141] J. Massion. Postural control systems in developmental perspective. *Neurosci. Biobehav. Rev.*, 22:465–472, 1998.

[142] K. Matsuoka. Sustained oscillations generated by mutually inhibiting neurons with adaptation. *Biological Cybernetics*, 52:345–353, 1985.

[143] D. Mayne, J.B. Rawlings, C.V. Rao, and P.O.M. Scokaert. Constrained model predictive control: stability and optimality. *Automatica*, 36(6):789–814, 2000.

[144] T. McGeer. Passive dynamic walking. *International Journal of Robotics Research*, 9(2):62–82, 1990.

[145] C.A. McGibbon and D.E. Krebs. Age-related changes in lower trunk coordination and energy transfer during gait. *J. Neurophysiol.*, 85:1923–1931, 2001.

[146] W.E. McIlroy and B.E. Maki. Changes in early automatic postural responses associated with the prior-planning and execution of a compasentory step. *Brain Res.*, 631:203–211, 1993.

[147] J. Mercier, D. Le Gallais, M. Durand, C. Goudal, J.P. Micallef, and C. Prefaut. Energy expenditure and cardiorespiratory responses at the transition between walking and running. *Eur. J. Appl. Physiol Occup. Physiol.*, 69:525–529, 1994.

[148] T. Mergner, D. Anastasopoulos, and Becker W. Neuronal responses to horizontal neck deflection in the group x region of the cat's medullary brainstem. *Experimental Brain Research*, 45(1-2):196–206, 1982.

[149] A.E. Minetti, L.P. Ardigo, and F. Saibene. Mechanical determinants of gradient walking energetics in man. *J. Physiol*, 472:725–735, 1993.

[150] A.E. Minetti, C. Moia, G.S. Roi, D. Susta, and G. Ferretti. Energy cost of walking and running at extreme uphill and downhill slopes. *J. Appl.P hysiol*, 93:1039–1046, 2002.

[151] H. Mittelstaedt and E. Fricke. The relative effect of saccular and somatosensory information on spatial perception and control. *Adv. Oto-Rhino-Laring*, 42:24–30, 1988.

[152] I. Miyai, H. Tanabe, I. Sase, H. Eda, I. Oda, I. Konishi, and et al. Cortical mapping of gait in humans: a near-infrared spectroscopic topography study. *NeuroImage*, 14:1186–1192, 2001.

[153] I. Miyai, H. Yagura, I. Oda, I. Konishi, H. Eda, T. Suzuki, and et al. Premotor cortex is involved in restoration of gait in stroke. *Ann. Neurol.*, 52:188–194, 2002.

[154] K.D. Mombaur, H.G. Bock, and J.P. Schlöder. Human-like actuated walking that is asymptotically stable without feedback. In *IEEE International Conference on Robotics & Automation*, pages 4128–4133, Seoul, Korea, May 2001.

[155] J. Monzani, P. Baerlocher, and D. Thalmann. Using an intermediate skeleton and inverse kinematics for motion retargeting. *EUROGRAPHICS*, 19(3), 2000.

[156] S. Nadeau, B. Amblard, S. Mesure, and D. Bourbonnais. Head and trunk stabilization strategies during forward and backward walking in healthy adults. *Gait and Posture, in press*, 2003.

[157] L.M. Nashner. Fixed patterns of rapid postural responses among leg muscles during stance. *Experimental Brain Research*, 30:13–24, 1977.

[158] L.M. Nashner and P. Cordo. Relation of automatic postural responses and reaction-time voluntary movements of human leg muscles. *Experimental Brain Research*, 43:395–405, 1981.

[159] L.M. Nashner, C.L. Shupert, F.B. Horak, and F.O. Black. Organization of posture controls: an analysis of sensory and mechanical constraints. *Prog. Brain. Res.*, 80:411–418, 1989.

[160] L. Newell and R. Emmerik. The acquisition of coordination : a preliminary analysis of learning to write. *Human movement science*, 8:17–32, 1989.

[161] Y. Nubar and R. Contini. A minimal principle in biomechanics. In *Bulletin of Mathematical Biophysics*, 1961.

[162] K.S. Olree and C.L. Vaughan. Fundamental patterns of bilateral muscle activity in human locomotion. *Biological Cybernetics*, 73(5):409–414, 1995.

[163] J. Paillard. Les determinants moteurs de l'organisation de l'espace. *Cahiers Psychol*, 14:261–316, 1971.

[164] J. Paillard. Fast and slow feedback loops for the visual correction of spatial errors in a pointing task: a reappraisal. *Can. J. Physiol. Pharmacol.*, 74:401–17, 1996.

[165] M.M. Panjabi, T.R. Oxland, I. Yamamoto, and J.J. Crisco. Mechanical behavior of the human lumbar and lumbosacral spine as shown by 3-dimensional load-displacement curves. *Journal of Bone and Joint Surgery - American*, 76A(3):413–424, 1994.

[166] D. Pérennou and B. Amblard. Man against gravity : the control of orientation and that of stabilisation are dissociated. *Exp Brain Res, in press*, 2004.

[167] D. Pérennou, B. Amblard, El M. Laassel, and J. Pélissier. Hemispheric asymmetry in the visual contribution to postural control in healthy adults. *NeuroReport*, 8:3137–3141, 1997.

[168] N. Petersen, J. Butler, V. Marchand-Pauvert, R. Fisher, A. Ledebt, H. Pyndt, and et al. Suppression of emg activity by transcranial magnetic stimulation in human subjects during walking. *J. Physiol.*, 532.2:651–656, 2001.

[169] F. Pfeiffer and C. Glocker. *Multibody Dynamics With Unilateral Contacts.* Wiley-Interscience Publication, John Wiley and Sons Inc., New York, NY, USA, 1996.

[170] F. Plestan, J.W. Grizzle, E.R. Westerwelt, and G. Abba. Stable walking of a 7-dof biped robot. *IEEE Trans. on Robotics and Automation*, 19(4):653–667, 2003.

[171] T. Pozzo, A. Berthoz, and L. Lefort. Head stabilization during various locomotor tasks in humans i. normal subjects. *Experimental Brain Research*, 82:97–106, 1990.

[172] B.I. Prilutsky and V.M. Zatsiorsky. Tendon action of two-joint muscles: transfer of mechanical energy between joints during jumping, landing, and running. *J. Biomech.*, 27:25–34, 1994.

[173] F. Prince, D.A. Winter, P. Stergiou, and S.E. Walt. Anticipatory control of upper body balance during human locomotion. *Gait & Posture*, 2-1:19–25, 1994.

[174] A. Prochazka. Sensorymotor gain control: a basic strategy of motor systems? *Prog. Neurobiol.*, 33:281–307, 1989.

[175] `http://www.sony.net/SonyInfo/QRIO/top_nf.html`.

[176] `http://robot-rabbit.lag.ensieg.inpg.fr/English/index.php`.

[177] M.H. Raibert. *Legged Robots that Balance.* MIT Press, 1986.

[178] A.J. Raynor, C.J. Yi, B. Abernethy, and Q.J. Jong. Are transitions in human gait determined by mechanical, kinetic or energetic factors? *Hum. Mov. Sci.*, 21:785–805, 2002.

[179] T.D.M. Roberts. *The role of vestibular and neck receptors in locomotion.* Herman RM, Grillner S, Stein PSG and Stuart DG (eds.) Neural control of locomotion. New York: Plenum, 1976.

[180] T.J. Roberts. The integrated function of muscles and tendons during locomotion. *Comp. Biochem. Physiol A Mol. Integr. Physiol*, 133:1087–1099, 2002.

[181] `http://www.robot.uvsq.fr/ProjetsLRV/ROBOCOQ/`.

[182] J. Rose and J.G. Gamble. *Human Walking.* William and Wilkins, Baltimore, USA, 1994.

[183] L. Roussel. *Génération de trajectoires optimales de marche pour un robot bipède.* PhD Thesis-INPG, France, 1998.

[184] R.H. Rozendal. *Biomechanics of standing and walking.* Bles, W., Brandt, Th. (Eds.). Elsevier, Amsterdam, New York, 1986.

[185] F. Saibene. The mechanisms for minimizing energy expenditure in human locomotion. *Eur. J. Clin. Nutr.*, 44 Suppl 1:65–71, 1990.

[186] P. Sardain, M. Rostami, and G. Bessonnet. *An Anthropomorphic Biped Robot: Dynamic Concepts and Technological Design*, volume 28-6. IEEE Trans. on Systems, Man, and Cybernetics, 1997.

[187] R.A. Schmidt, H. Zelaznik, B. Hawkins, J.S. Frank, and J.T. Jr. Quinn. Motor-output variability: a theory for the accuracy of rapid motor acts. *Psychol. Rev..*, 47(5):415–451, 1979.

[188] K. Schneider, R. Zernicke, R. Schmidt, and T. Hart. Changes in limb dynamics during the practice of rapid arm movements. *Journal of biomechanics*, 22:805–817, 1989.

[189] J.P. Scholz and G. Schøner. The uncontrolled manifold concept : identifying control variables for a functional task. In *Exp. Brain. Res.*, pages 289–306, 1999.

[190] `http://www.shadow.org.uk/projects/biped.shtml`.

[191] J.F. Soechting and M. Flanders. *Deducting central algorithms of arm movement control from kinematics.* Humphrey DR, Freund HJ (Eds) John Wiley and Sons, Chichester, UK, 1991.

[192] `http://www.ai.mit.edu/projects/leglab/robots/Spring_Flamingo/Spring_Flamingo.html`.

[193] G. Taga, Y. Yamaguchi, and H. Shimizu. Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment. *Biol. Cybern.*, 65(3):147–159, 1991.

[194] E. Thelen, R. Zernicke, K. Schneider, J. Jensen, K. Kamm, and D. Corbetta. *The role of intersegmental dynamics in infant neuromotor development.* Elsevier, Science Publishers, 1992.

[195] B. Thomachot, B. Amblard, and H. Roux. *Stabilisation latérale du rachis lors de la marche chez le sujet sain et le spondylarthritique.* Simon, L.;, Pélissier, J.;, Hérisson, Ch., (Eds.) Actualités en Rééducation fonctionnelle et Réadaptation. Paris: Masson, 1995.

[196] N.F. Troje and B.J. Frost. Head-bobbing in pigeons: how stable is the hold phase? *J. Exp. Biol.*, 203:935–940, 2000.

[197] `http://www.ai.mit.edu/people/chunks/index.html`.

[198] H. VanDerKooij. *Human Balance Control in standing and walking.* Phd thesis, Thesis-Twente University, 2000.

[199] C.L. Vaughan. Theories of bipedal walking: an odyssey. *J. of Biomechanics*, 36:513–523, 2003.

[200] C.L. Vaughan, B. Davis, and J.C. O'Connor. Dynamics of human gait. In *Human Kinetics.* Champaign, 1992.

[201] S. Vernazza-Martin, N. Martin, and J. Massion. Kinematic synergies and equilibrium control during trunk movement under loaded and unloaded conditions. *Exp Brain Res.*, 128(4):517–526, 1999.

[202] M. Vukobratović, B. Borovav, D. Surla, and D. Stokić. *Biped Locomotion: Dynamics, Stability, Control and Application.* Springer-Verlag, London, Great Britain, 1990.

[203] `http://www.takanishi.mech.waseda.ac.jp/wabian/2003_e_1.html`.

[204] R.C. Wagenaar and R.E. van Emmerik. Resonant frequencies of arms and legs identify different walking patterns. *J. Biomech.*, 33(7):853–861, 2000.

[205] T. Wannier, C. Bastiaanse, G. Colombo, and V. Dietz. Arm to leg coordination in humans during walking, creeping and swimming activities. *Exp. Brain Res.*, 141(3):375–379, 2001.

[206] R.L. Waters and S. Mulroy. The energy expenditure of normal and pathologic gait. *Gait. Posture.*, 9:207–231, 1999.

[207] E.R. Westervelt, G. Buche, and J.W. Grizzle. Inducing dynamically stable walking in an underactuated planar biped. In *IEEE International Conference on Robotics & Automation*, pages 4234–4239, New Orleans, USA, April 2004.

[208] M.W. Whittle. Clinical gait analysis: a review. In *Human Movement Science*, volume 15, pages 369–387, 1996.

[209] P. B. Wieber. Constrained dynamics and parametrized control in biped walking. In *Proceedings of the International Symposium on Mathematical Theory of Networks and Systems*, 2000.

[210] P. B. Wieber. On the stability of walking systems. In *Proceedings of the International Workshop on Humanoid and Human Friendly Robotics*, 2002.

[211] P. B. Wieber and C. Chevallereau. Online adaptation of reference trajectories for the control of walking systems. *Submitted*, 2004.

[212] P.B. Wieber. *Modélisation et Commande d'un Robot marcheur Anthropomorphe.* PhD Thesis-École Nationale Supérieure des Mines de Paris, France, 2000.

[213] M. Williamson. Neural control of rythmic arm movements. *Neural Networks*, 11(7-8):1379–1394, 1998.

[214] D.A. Winter. *Biomechanics and motor control of human gait.* Waterloo, Ont.: University of Waterloo Press, 1987.

[215] D.A. Winter. *Biomechanics and Motor Control of Human Movement.* New York: John Wiley & Sons, 1990.

[216] D.A. Winter. *ABC (Anatomy, Biomechanics and Control) of Balance During Standing and Walking.* Waterloo, Ontario: waterloo Biomechanics, 1995.

[217] D.M. Wolpert. Computational approaches to motor control. *Trends in Cognitive Sciences*, 1-6:209–216, 1997.

[218] D.M. Wolpert, C. Miall, and M. Kawato. Internal models in the cerebellum. *Trends in Cognitive Sciences*, 9:338–347, 1998.

[219] F.E. Zajac, R.R. Neptune, and S.A. Kautz. Biomechanics and muscle coordination of human walking. part i: introduction to concepts, power transfer, dynamics and simulations. *Gait and Posture*, 16:215–232, 2002.

[220] P. Zamparo, R. Perini, C. Orizio, M. Sacher, and G. Ferretti. The energy cost of walking or running on sand. *Eur.J.Appl.Physiol Occup.Physiol*, 65:183–187, 1992.

[221] V.M. Zatsiorsky, S.L. Werner, and M.A. Kaimin. Basic kinematics of walking. In *The Journal of Sports Medicine and Physical Fitness*, volume 34-(2), pages 109–134, June 1994.

Unité de recherche INRIA Sophia Antipolis
2004, route des Lucioles - BP 93 - 06902 Sophia Antipolis Cedex (France)

Unité de recherche INRIA Futurs : Parc Club Orsay Université - ZAC des Vignes
4, rue Jacques Monod - 91893 ORSAY Cedex (France)
Unité de recherche INRIA Lorraine : LORIA, Technopôle de Nancy-Brabois - Campus scientifique
615, rue du Jardin Botanique - BP 101 - 54602 Villers-lès-Nancy Cedex (France)
Unité de recherche INRIA Rennes : IRISA, Campus universitaire de Beaulieu - 35042 Rennes Cedex (France)
Unité de recherche INRIA Rhône-Alpes : 655, avenue de l'Europe - 38334 Montbonnot Saint-Ismier (France)
Unité de recherche INRIA Rocquencourt : Domaine de Voluceau - Rocquencourt - BP 105 - 78153 Le Chesnay Cedex (France)

Éditeur
INRIA - Domaine de Voluceau - Rocquencourt, BP 105 - 78153 Le Chesnay Cedex (France)
http://www.inria.fr
ISSN 0249-6399