Control of Biped Walking Based on Force Interaction

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Abstract

The focus of this paper is the problem of modelling and control of a biped robot by combining Cartesian-based position and force control algorithms. The walking cycle is divided in two phases: single support, in which one leg is in contact with the ground and the other leg swings forward, and double support, in which the forward leg absorbs the impact and gradually accepts the robot's weight. The contact of the foot with the constrained surface is modelled through linear and nonlinear spring-damper systems. The proposed control approach is based on simple motion goals taking into account the reaction forces between the feet and the ground. The control algorithm is tested through several experiments and its effectiveness is discussed.

1 Introduction

Nowadays, many aspects of modern life involve the use of intelligent machines capable of operating under dynamic interaction with its environment. The field of biped locomotion is representative of this interest concerning human-like robots [1-4]. In the last years, a growing community of researchers is working towards a better understanding of the motor control principles and the sensory integration subjacent to machines that can balance, strike purposively and coordinate multiple degrees of freedom [5-7]. However, in order that such a systems have an effective application, its control and computing complexity must be reduced, whilst new technological developments are emerging.

The major problems associated with the analysis and control of bipedal systems are the high-order, highly coupled nonlinear dynamics and, furthermore, the discrete changes in the dynamic phenomena due to the nature of the walking gait. At the same time, the degree of freedom (dof) formed between the foot and the ground is unilateral and underactuated [8]. This paper addresses the problem of modelling and control of a biped robot by combining Cartesian-based position and force control algorithms. The main goal is to analyse the dynamic phenomena that emerge from the physical interaction between the robot and the environment based on force-compliance algorithms.

The remainder of the paper is organised as follows. Section 2 describes the implementation of both biped and environment models. Section 3 addresses the motion planning problem. Section 4 is dedicated to control issues and the associated strategies. Section 5 studies the application of the proposed algorithm and presents the simulation results. Section 6 concludes this paper and outlines the perspectives towards future research.

2 Biped Model

Figure 1 shows the planar biped model with two lower limbs and an upper body (*i.e.*, trunk, pelvis, thigh, shank and feet). The model considers ideal actuators at all joints including the ankles. Moreover, it is studied a symmetric and periodic gait divided in two phases:

i) Single-support phase (SS) in which one leg is in contact with the ground and the other leg swigs forward.

ii) Double-support phase (DS) in which the legs gradually trade role.

In the SS phase, the stance leg is in contact with the ground and carries the weight of the body, while the swing leg moves forward in preparation for the next step. In the DS phase, the swing leg is in contact with the ground and, gradually, accepts the robot's weight.

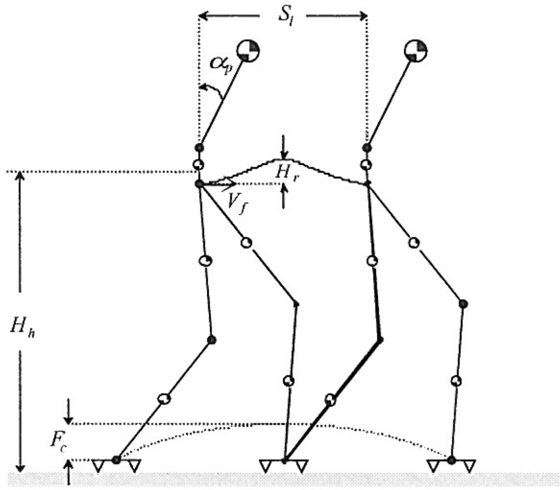


Figure 1: Planar biped model.

2.1 Environment model and sensors

The contact of the feet with the constraint surface is modelled through a linear spring-damper in the horizontal direction and a linear spring with a nonlinear damper in the vertical direction. The tangential and normal reaction forces applied to the foot are computed as:

$$\begin{aligned} f_t &= -B_x \dot{x} - K_x (x - x_0) \\ f_n &= -\lambda \delta y \dot{y} - K_y (y - y_0) \end{aligned} \tag{1}$$

where B_x and K_x, K_y are the damping coefficient and the spring stiffness, respectively, λ is a constant, δy is the penetration depth (Table A) and x_0, y_0 are the coordinates of the foot at the moment of its initial contact.

Table A Environment parameters.

B_x (Ns/m)	K_x (N/m)	K_y (N/m)	λ (Ns/m^2)
5.0×10^3	5.0×10^4	5.0×10^5	7.5×10^6

It is assumed the existence of two contact points located in the extremities of the foot, as illustrated in Figure 2. Moreover, under each foot are inserted two force sensors (at the toe and across the heel) that provide an indication of both contact with the ground and distribution of forces.

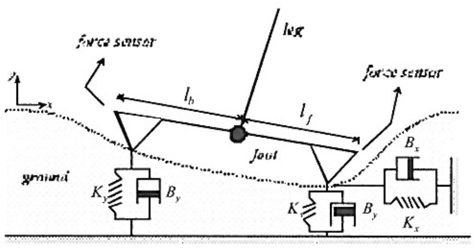


Figure 2: Constraint environment model.

2.2 Dynamics of the biped robot

A biped robot is a mechanism that repeatedly interacts with the environment through their feet. In this line of thought, the dynamic equations of motion are derived assuming the contact of both legs with the ground:

$$\tau = H(q)\ddot{q} + c(q,\dot{q}) + g(q) - J_R^T f^R - J_L^T f^L \tag{2}$$

where τ is the vector of generalised torques, q is the vector of joint coordinates, $H(q)$ is the inertial matrix, $c(q,\dot{q})$, is the vector of centrifugal/Coriolis torques and $g(q)$ is the vector of gravitacional torques. The transpose of the Jacobian matrices, J_R^T and J_L^T, transform the external forces, f^R and f^L, that the environment exerts on the right (R) and left (L) foot into joint torques.

The internal parameters of the robot comprise a total mass of $M = 37kg$ and a maximum height of $L = 1.4m$ (see Table B).

Table B The robot link lengths and masses.

Link	Length (m)	Mass (kg)
Body	0.3	10.0
Pelvis	0.1	2.0
Thigh	0.5	7.5
Shank	0.5	4.0
Foot	0.2	1.0

3 Motion Planning

The motion planning is accomplished by prescribing the Cartesian trajectories of the hip and lower extremity of the swing leg. For that objective, the biped motion is characterised in terms of a set of locomotion variables, such as step length S_l, hip height H_h, hip ripple H_r, hip pitch angle α_p, foot clearance F_c and forward velocity V_f (Figure 1). These locomotion variables are directly related with a set of high level motion goals, such as:

1) To maintain a constant forward velocity or, alternatively, to apply a small horizontal oscillation.
2) To maintain a constant hip height or, alternatively, to apply a small vertical oscillation.
3) To place the foot on the ground with zero velocity in order to reduce the impact effects.
4) To lift the foot above the ground to avoid obstacles.

Then, the trajectory generator synchronises and coordinates the legs using cycloid profiles and other sinusoidal time functions.

3.1 Stability condition

The rotational equilibrium of the foot is the major factor of postural instability in legged robots. This question has motivated the definition of several dynamic-based criteria for the evaluation and control of balance in biped locomotion. The most common criteria are the centre of pressure (CoP), the zero moment point (ZMP) and the foot rotation indicator (FRI), defined as follows [8]:

1) The CoP is a point P on the foot/ground surface where the net ground reaction force actually acts.
2) The ZMP is the point on the floor at which the moment generated by the reaction force and the reaction torque are balanced.
3) The FRI point is a point F on the foot/ground surface, inside or outside the base of support, where the net ground reaction force would have to act to keep the foot stationary.

Although the concept of ZMP is identical to the CoP, the assumption of a deformable foot/ground contact means that the two points do not necessarily coincide. At this stage, the physical realisability of the specified motion is imposed by an appropriated reference CoP, while the condition of stable contact is expressed as:

$$f_{heel} > 0 \text{ and } f_{toe} > 0 \qquad (3)$$

where f_{heel} and f_{toe} are the normal ground reaction forces at the toe and across the heel.

4 Position/Force Hybrid Control

The essence of locomotion is to transport the upper body from an initial position to a desired one throughout the action of the lower limbs. The biped's movement is produced by ideal power actuators and constrained by environmental aspects. The resultant motion depends on two factors, namely, the structural and functional characteristics of the intelligent controller and the physical phenomena such as gravity, friction and reaction forces.

Bearing these facts in mind, it is proposed a hybrid position/force controller to achieve Cartesian tracking control and force compliance with the ground. The block diagram of the global control architecture is shown in Figure 3. The relevant aspects of the GO-FIC are the minimal dependence on planned variables and the consideration of the reaction forces at the feet extremities on the control algorithm. In other words, the biped robot "feels" the forces while the controller distributes them as driving torques that regulate the body's motion.

The structure of the controller takes the form of a hybrid position/force algorithm that switches between the force control, for the stance leg, and the position control, for the swing leg. When the swing foot contacts the ground, additional force control efforts are used in the forward leg to stabilise the post-impact phase and to provide for a smooth transfer of support. In what concerns the upper body, two main goals should be achieved with the positional control: to keep the upright stability of the pelvis and to follow a desired horizontal hip trajectory.

4.1 Force distribution

The ground reaction forces combine both the gravity acting on the system and the accelerations of all body segments. In this perspective, the desired normal forces are computed on-line as the sum of the robot's weight with a compensation term, that is:

$$f_n^{ref} = B.W. + \left[K_p^y\left(y_h^d - y_h\right) + K_v^y\left(\dot{y}_h^d - \dot{y}_h\right)\right] \qquad (4)$$

Here f_n^{ref} is the reference normal force, *B.W.* is the total system's weight, y_h^d and y_h are the desired and real hip vertical position, $\dot{y}_h^d$ and $\dot{y}_h$ are the corresponding velocities, respectively. This means that vertical errors at the hip are transformed into modifications of the reference force around its average value.

During the SS phase, the reference CoP is actively used to calculate the distribution of the total reaction force along the two extremities of the stance foot. However, in the DS phase the question is how to solve the force distribute between legs that allows a smooth transition of support.

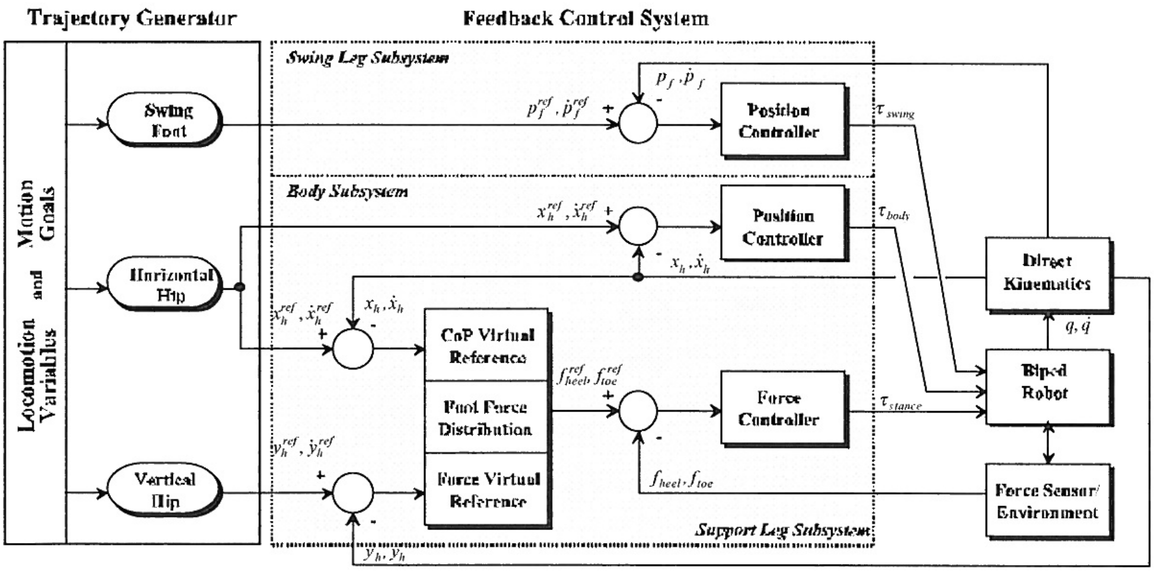


Figure 3: Goal-Oriented Force Interaction Control (GO-FIC).

Given the virtual reference in (4), a simple method is used in which the legs gradually (linear function) trade role. At the same time, the reference CoP has proved useful in minimising the power consumption. From this point of view, its optimal evolution is inferred from the hip horizontal position/velocity errors. To assure the complete stability of the foot, we apply a saturation filter that limits the CoP to a given stability margin.

We are concerned with command forces in the y-direction but not in the x-direction (friction is assumed to be sufficiently large). As a consequence, the hip trajectory tracking is not achieved in the horizontal direction. In this case, the movement of the trunk helps to regulate the horizontal behaviour. For that, the associated power actuator uses the following control law:

$$\tau = K_p^x\left(x_h^d - x_h\right) + K_v^x\left(\dot{x}_h^d - \dot{x}_h\right) \quad (5)$$

4.2 Control strategies

This section describes the most important aspects of the controller implementation. The main problem is the selection of the individual contributions that provide coordinated gaits and a steady dynamic walking. The performance imposed by the particular task to be accomplished shall dictate the importance of each component. The information flows in the different phases of the walking cycle as depicted in Figure 4. Two dynamic selection gains S_R and S_L determine the instants for which force and/or position are controlled in the right and left legs, respectively. The corresponding values depend on the particular phase of the walking cycle.

Following the controller activity illustrated in Figure 4:

1) Single support - the right leg is force controlled and the swing foot is position controlled.
2) Initial phase of the double support - the selection gain S_L assures a transition period in which the controller changes linearly from position to force.
3) Final phase of the double support - the selection gain S_R assures a transition period in which the controller changes linearly from force to position.

At each footfall the walking system suffers impact forces and incur on additional accelerations. In order to reduce these effects, it was adopted a swing phase that minimises the impact velocities. Moreover, in the course of each stride the swing leg must flex to absorb the impact energy and, afterwards, become stiff as the support is shifted from the trailing to the leading legs. Additionally, the position/velocity references are modified immediately after the foot impact and the lift up occurs.

Similarly, the selection gain S_H is responsible for the coordination of the hip joints. During the SS phase, the left hip helps to regulate the swing foot trajectory whilst the right hip assures the pelvic stability. In contrast, in the DS phase the hip actuators help together to control the upright posture of the pelvic segment.

The control laws are designed independently: the position control law consists of a PD action and the force control law consists of a PI action. It is introduced an enhancement to the PI force controller by adapting its controller gains during the DS phase in accordance with the distribution of forces between legs.

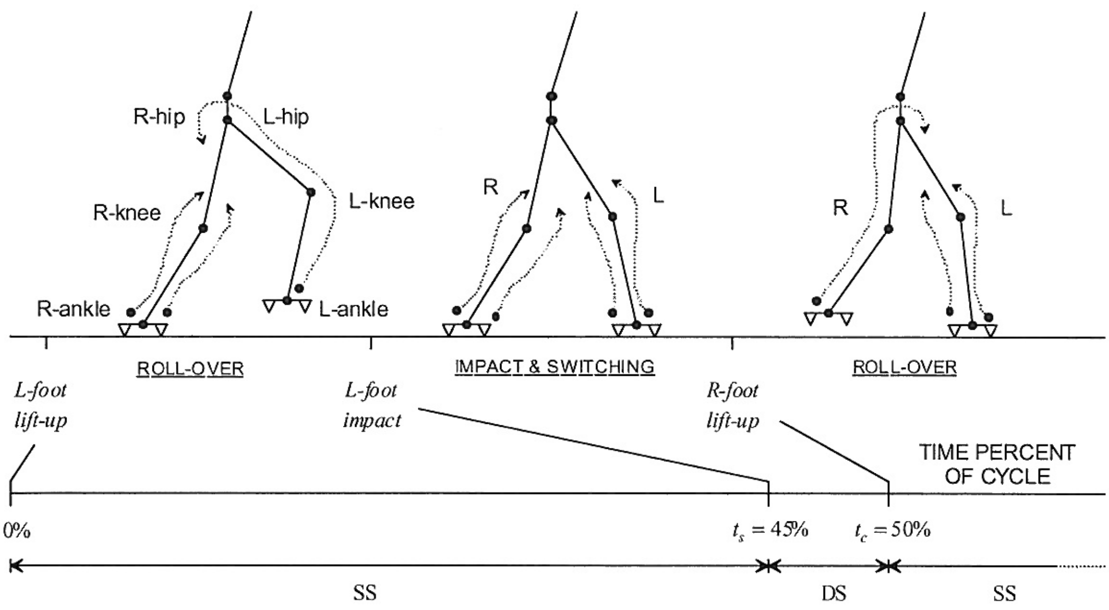


Figure 4: Controller activity and information flow during half a cycle.

5 Simulation Results

When the motion of the biped robot is selected according to a given performance criterion (*e.g.*, minimal lost power), the effects of the planned reference trajectories are usually not evident, because their merits or drawbacks may be overridden by the controller's actions. Nevertheless, an adequate motion planning can still ease the controller efforts and helps the locomotion process [9]. The next simulations are carried out assuming the locomotion variables presented in Table C.

Table C Locomotion variables.

$S_l\,(m)$	$H_h\,(m)$	$H_r\,(m)$	$F_c\,(m)$	$V_f\,(m/s)$
0.4	0.95	0.07	0.02	1.0

To illustrate the control strategies, the biped robot is simulated during one complete cycle (two steps) for a sampling controller frequency $f_c = 10KHz$. We assume that: *i*) the biped starts the movement $t = 0$ with the lift off the ground of the rear foot; *ii*) the swing foot strikes the ground at $t_s \approx 0.36s$; and *iii*) the support transition occurs at $t_c = 0.4s$. The computed joint torques are depicted in Figure 5. From these charts, we conclude that the controller is effective to regulate the impact transitions. At the same time, the application of the direct force feedback algorithm solves the force distribution problem and assures continuous torques. Figure 6 represents the CoP trajectory of the biped robot along two consecutive steps.

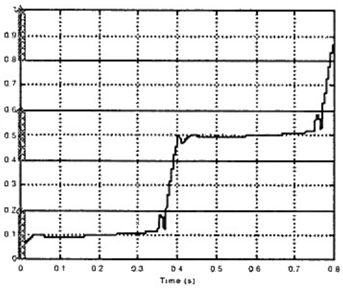


Figure 6: CoP trajectory during one complete cycle.

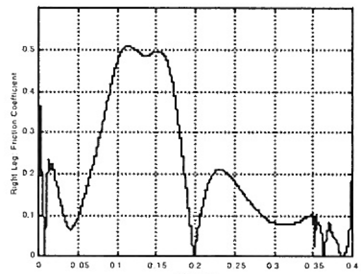


Figure 7: Friction coefficient to avoid sliding (right leg).

During the SS phase the CoP is inside the support covered by the stance foot and then, during the DS, it moves continuously into the other foot. At the same time, the force controller is effective in accomplishing a smooth transfer of weight (Figure 5), while the friction coefficient condition to avoid sliding is $\mu > 0.5$ (see Figure 7). The trajectory following errors at the hip coordinate are shown in Figure 8(*a*). Finally, the phases of contact and lift-up in which the legs trade role are illustrated in Figure 8(*b*).

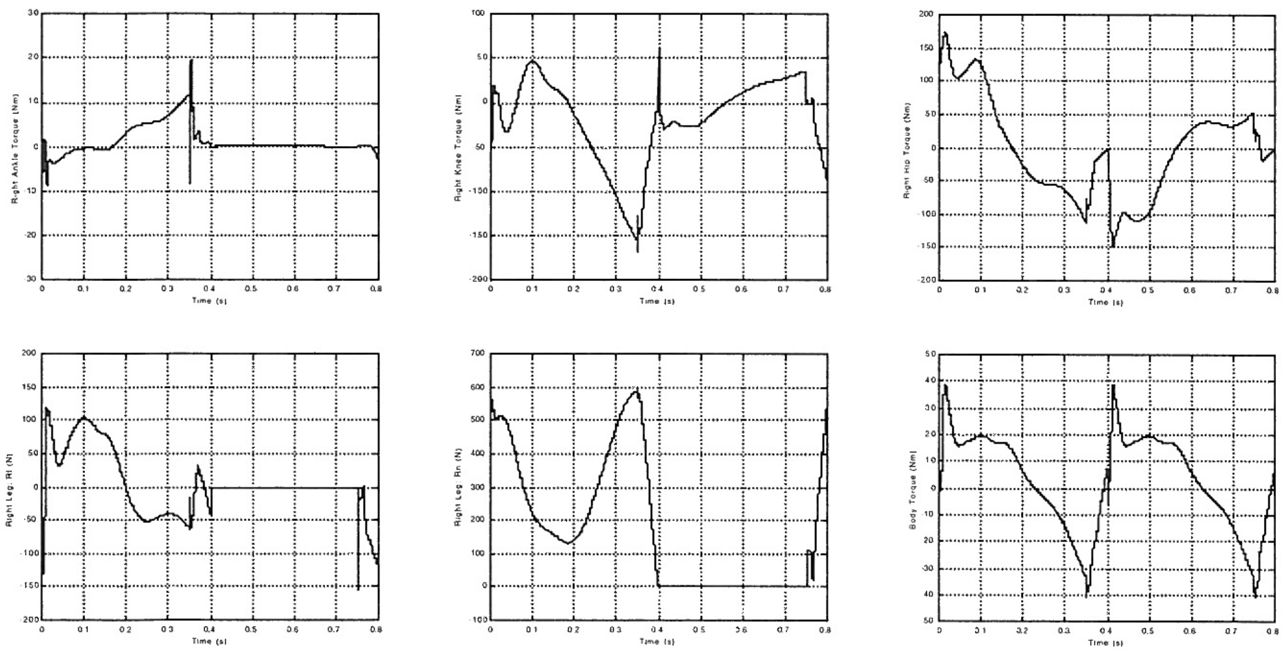
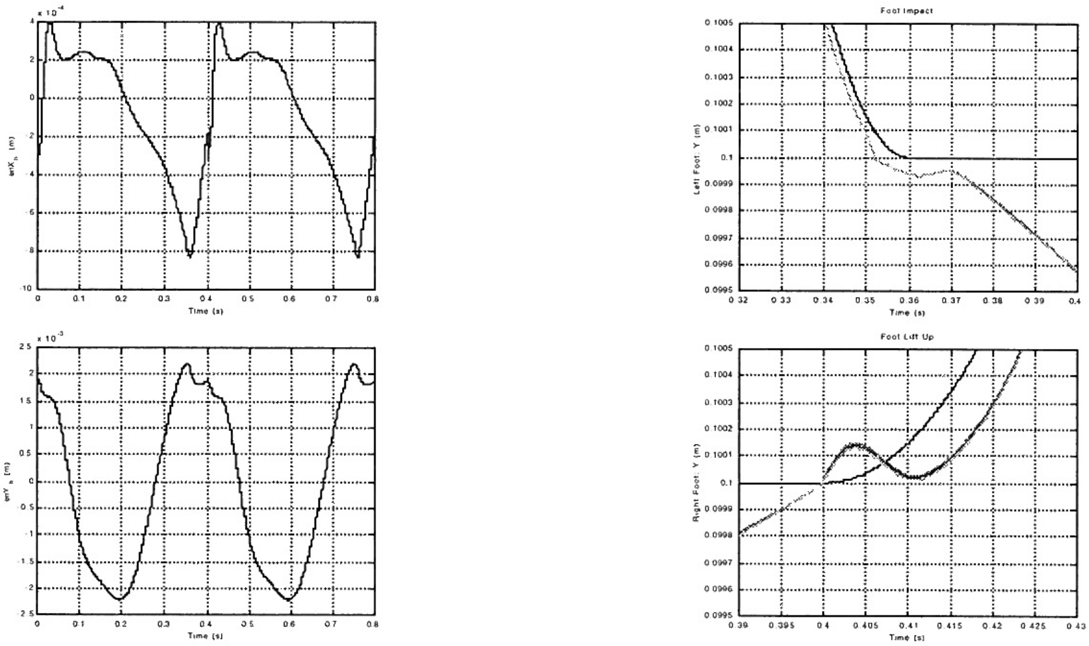


Figure 5: Joint torques and ground reaction forces during one complete cycle.



(*a*) (*b*)

Figure 8: (*a*) Position errors at the hip coordinate; (*b*) foot impact and lift-up (ground level is $0.1m$).

6 Conclusions

This paper has investigated the combination of position and force control algorithms. The results suggest the following major comments. First, the GO-FIC is well adapted to achieve foot stability, force compliance and different motion goals. Second, the application of the force feedback algorithm allows a smooth transfer of weight. Moreover, an adequate force distribution along the landing foot assures continuous torques. Third, the combination of position and force information results in a steady dynamic walking. However, the system's performance depends strongly on the foot trajectory. This fact suggests the incorporation of some kind of compliant feet.

Ongoing research focuses in two main directions: *i*) to apply the proposed method to different walking tasks; and *ii*) to incorporate a mechanism of adaptation to different environments. A practical biped needs to be more like a human – switching between different known gaits on familiar terrain and learning new gaits when presented with unknown terrains. In this sense, it seems essential to combine force control techniques with more advanced algorithms such as adaptive and learning strategies.

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