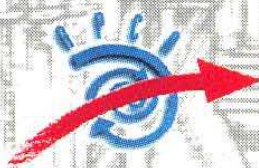


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POSITION/FORCE CONTROL OF BIPED LOCOMOTION SYSTEMS

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Abstract: This paper addresses 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 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 and robustness is discussed. *Copyright CONTROLLO 2000*

Keywords: trajectory planning, dynamics, control algorithms, force control, walking

1. INTRODUCTION

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. A growing community of researchers is working towards a better understanding of machines that can balance, strike purposively and coordinate multiple degrees of freedom (Fujimoto *et al.*; 1996, Hirai, *et al.*, 1998; Pratt *et al.*, 1998; Raibert, 1986; Yamaguchi, *et al.*, 1999). 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 surface is unilateral and underactuated (Goswami, 1999).

This paper addresses the problem of modelling and control of a biped robot by combining Cartesian-based position and force control algorithms. The aim of the study is to analyse the dynamic phenomena that make the robot able to adapt to its environment based on force-compliance algorithms.

In this line of thought, the remainder of the paper is organised as follows. Section 2 describes briefly 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 algorithms and presents 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, we consider that the locomotion consists of a periodic process where a walking cycle is 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.

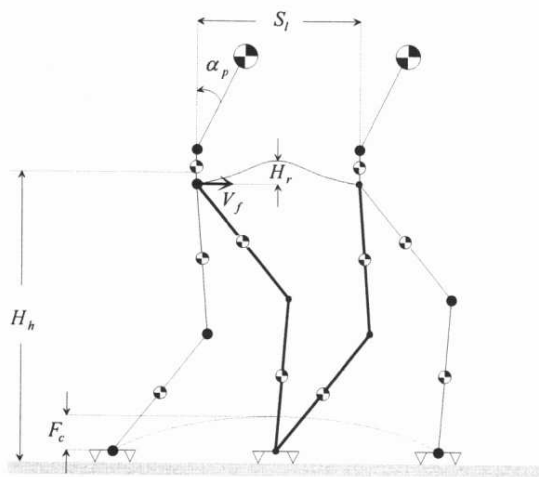


Fig. 1. Planar biped model.

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.

2.1 Environment Model and Sensorial Requirement

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

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

where B_x, B_y and K_x, K_y are the damping coefficient and the spring stiffness, respectively, and (x_0, y_0) is the coordinate of the foot at the moment of its initial contact. The parameters of the model are summarised in Table 1.

Table 1 Environment parameters.

B_x (Ns/m)	K_x (N/m)	B_y (Ns/m)	K_y (N/m)
5.0×10^3	5.0×10^4	5.0×10^2	1.0×10^6

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.

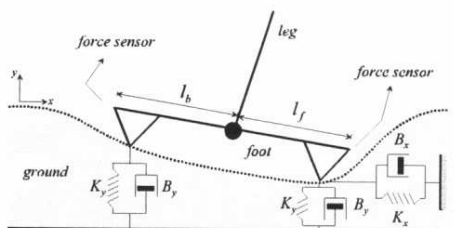


Fig. 2. Constraint environment model.

2.2 Dynamics of the Biped Robot

A biped robot is a mechanism that repeatedly interacts with the environment through their feet. The point of contact is not fixed and, furthermore, the dof formed between the foot and the ground are underactuated. In this line of thought, the dynamic equations of motion are derived assuming the contact of both legs with the ground:

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

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 gravitational 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 parameters of the robot comprise a total mass of $M = 37\text{kg}$ and a maximum height of $L = 1.4\text{m}$ (Table 2).

Table 2 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, body and lower extremities of the swing leg. These coordinates 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.

In this sense, the biped motion is first 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). Then, the trajectory generator synchronises and coordinates the legs using cycloid profiles and other sinusoidal time functions.

3.1 Stability Conditions

The rotational equilibrium of the foot is the major factor of postural instability in legged robots (Goswami, 1999). This question has motivated the definition of a dynamics-based criterion for the evaluation and control of balance of the legged system.

Two common criteria used in biped locomotion are the centre of pressure (CoP) and the foot point indicator (FRI), that can be defined as follows:

- 1) The CoP is a point P on the foot/ground surface where the net ground reaction force actually acts. With respect to a reference coordinate origin O :

$$OP = \frac{\sum r^i f_n^i}{\sum f_n^i} \quad (3)$$

- 2) 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.

An explicit expression for the coordinates of the point F is obtained by manipulating the dynamic equilibrium equation of the foot. Whenever the foot contact is stable, the FRI point is inside the support line and it coincides with the CoP. On the other hand, the exit of the FRI from the support line signals an unbalanced moment on the foot, whereas the CoP is at the polygon boundary.

At this stage, the physical realisability of the prescribed motion is evaluated based on the FRI criterion. To assure the complete stability of the foot, it is proposed the application of a saturation filter as shown in Figure 3. As result, the FRI trajectory is constrained to be inside the foot support line, with a specified stability margin S_m (this means that FRI = CoP).

3.2 Force Distribution

The ground reaction forces combine both the gravity acting on the system and the accelerations of all body segments. During the SS phase, the desired CoP is actively used to calculate the distribution of the total reaction force along the stance foot (*i.e.*, between the two extremities of the foot). However, in the DS phase a pertinent question is how to solve the force distribute between legs that allows a smooth transition of support. Given the redundancies in (2), a simple method is used by specifying the reaction forces for one leg (using a linear function) and solving for the other. At the same time, to satisfy the torque continuity at the end of the first step the CoP of the front leg is also specified. Afterwards, the foot/ground friction is assumed to be sufficiently large to avoid sliding.

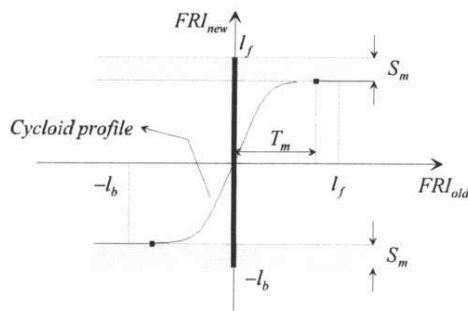


Fig. 3. Saturation filter applied to the FRI trajectory.

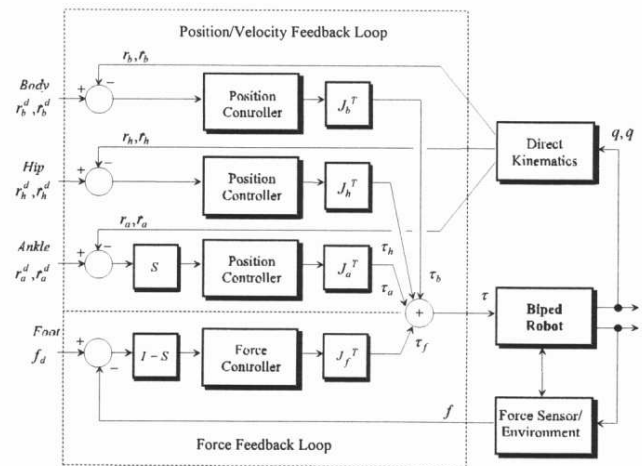


Fig. 4. Hybrid Position/Force Controller.

4. POSITION/FORCE HYBRID CONTROL

The essence of locomotion is to transport the 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 position/velocity tracking control and force compliance with the ground.

The block diagram of the hybrid control algorithm is shown in Figure 4. The relevant aspect is the consideration of the reaction forces between the feet and the ground on the control algorithm. The biped robot "feels" the forces while the controller distributes them as driving torques that regulate the body 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 pitch trajectory.

4.1 Hip Motion Compensation

The reference forces acting at the extremities of the feet are computed off-line as described above (section 3.2). In order to improve the foot contact stability, we are concerned with command forces in the y -direction but not in the x -direction. As a consequence, the hip trajectory tracking is not achieved due to small but accumulative errors. The proposed strategy can be decomposed into vertical and horizontal directions.

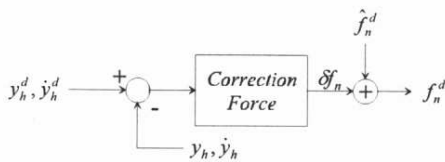


Fig. 5. Modification of the reference force.

On one side, the vertical errors are transformed into modifications of the reference force (Figure 5):

$$f_n^d = \hat{f}_n^d + [K_p^y(y_h^d - y_h) + K_v^y(\dot{y}_h^d - \dot{y}_h)] \quad (4)$$

Here f_n^d and \hat{f}_n^d are the modified and original normal reaction forces, 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.

On the other side, the movement of the trunk helps to regulate the horizontal behaviour. In this sense, the associated power actuator uses the following control law:

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

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. At the same time, the performance imposed by the particular task to be accomplished (e.g., normal walking, climbing stairs) shall dictate the importance of each component. This study focuses the implications of the body, hip and feet in normal walking. The information flows in the different phases of the walking cycle as depicted in Figure 6.

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 represented in Figure 6:

- 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 the impact effects it was adopted a minimisation strategy of the impact velocities. Additionally, 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.

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 (see Figure 6). 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.

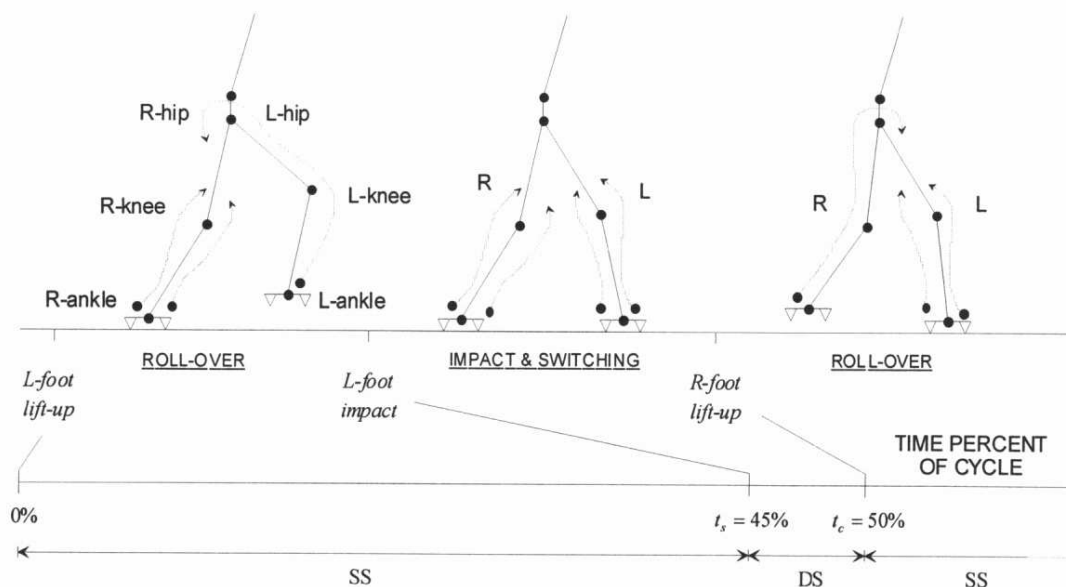


Fig. 6. Controller activity and information flow during half a cycle.

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 execution of the locomotion process. A complete analysis of the power performance can be found in other articles by Silva and Tenreiro (1999). The next simulations are carried out assuming the locomotion variables presented in Table 3.

Table 3 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 along a complete walking cycle for a sampling controller frequency $f_c = 10\text{KHz}$. 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 $t_s \approx 0.36\text{s}$; and *iii*) the support transition occurs at $t_c = 0.4\text{s}$. Figure 7 shows the results of the simulation as a stick diagram.

The computed joint torques are depicted in Figure 9. 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.

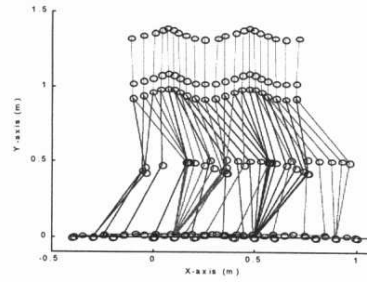


Fig. 7. Stick diagram.

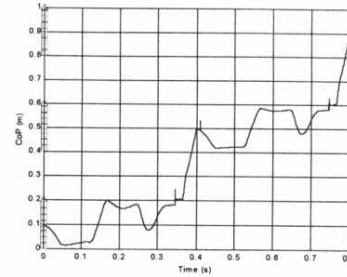


Fig. 8. CoP trajectory along a walking cycle.

Figure 8 represents the CoP trajectory of the biped robot along the walking cycle. In 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 10(a-b)), and to compensate for any deviation in the hip coordinates (Figure 10(c)). Although not controlled, the horizontal reaction forces follow approximately the desired ones giving rise to small compensatory motions of the trunk.

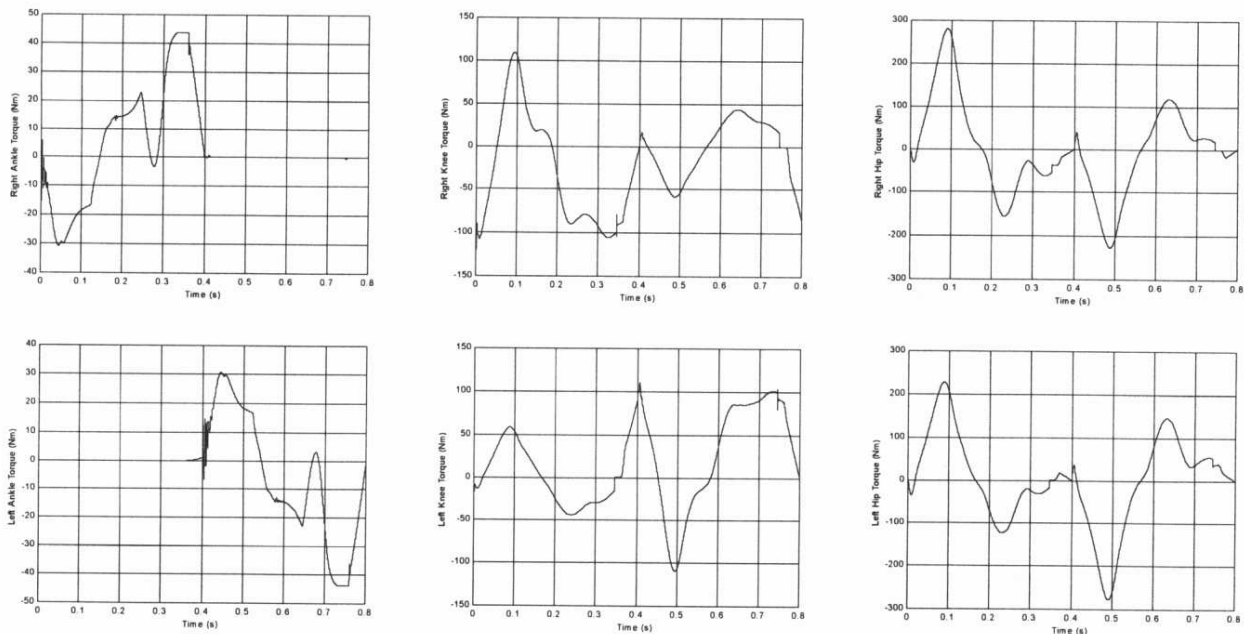


Fig. 9. Ankle, knee and hip torques during one walking cycle.

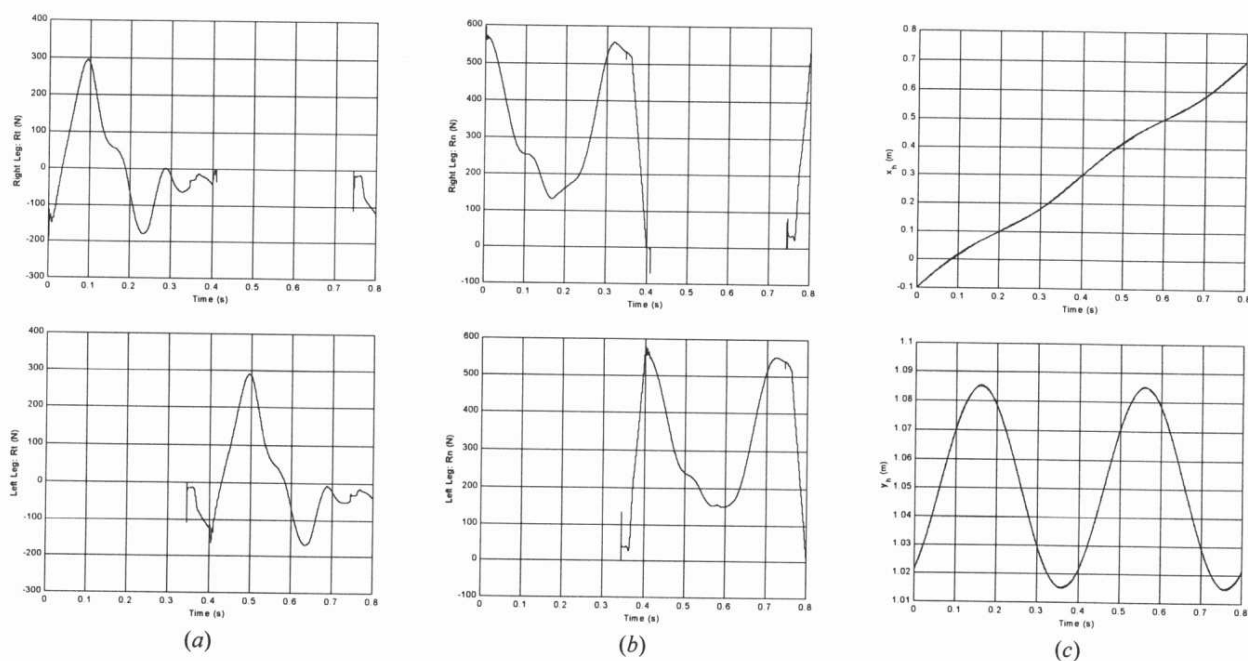


Fig. 10. (a) tangential and (b) normal reaction forces on both legs; (c) reference and real hip coordinates.

6. CONCLUSIONS

This paper has investigated the combination of position and force control algorithms. The results suggest three major comments. First, the force controller is well adapted to achieve foot stability, force compliance and forward velocity control. Second, the application of the direct 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 consideration of active compliant feet (*i.e.*, biological-like) with some kind of shock absorption mechanism.

The research should continue in two main directions: *i*) to minimise the dependence on high level planned motions 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 fundamental force control techniques with more advanced algorithms such as adaptive and learning strategies.

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