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Behavioural approach for a bipedal robot stepping motion gait

F. El Hafi,* P. Gorce,*,**

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SUMMARY

This paper deals with the decision mechanism analysis and the design of bipedal trajectories, for the stepping motion. For that we have used biomechanical model of the human body and dynamic control scheme previously developed by Gorce.[1] We based our study on an experimental protocol, in order to determine behavioural laws for the task execution. We have developed a biped trajectory generation process, taking into account the biped height and the obstacle dimensions. Furthermore, we characterize the stepping motion feasibility by introducing a security notion, and we define an "Admissible control Domain", which relies on the relative position of the biped to the obstacle and the obstacle dimensions. This domain definition has led us to define the biped behavioural strategies facing an obstacle: the biped executes the task at an accurate "chosen distance", or stops or takes another way. Experimentations have allowed to validate simulations results.

KEYWORDS: Bipedal robot; Stepping motion; Admissible control domain; Behavioural.

1. INTRODUCTION

In robotics field as well as in biomechanic field, many studies and human models have been developed to better understand the human behavioural mechanisms in various situation: walking,[2,3] running,[4] etc. Two aspects have been generally taken into account to solve the human locomotion control: the human body model, and the dynamic or kinematics issues:

a. Human models: Firstly, 2D plane models have been developed to study the gait in the sagittal plan, made of two link inverse pendulum model,[5] or three links model[6] or four link model.[7] Secondly, 3D models that represent more realistic structure of the human body have been developed composed by inverse pendulum models,[8] or eight links models[9] or more complex model composed of nine links.[10] Also, additional systems have been evaluated as well as the possibility of adding muscles or neuro-musculo-skeletal models to the system.[11–13]
b. Several approaches have been developed to control the kinematic and the dynamic issues in locomotion with human body complexity.[14–16] Different methods were evaluated, the concept of ZMP was introduced in quasi-dynamic gait, by Vukobratovic and Stepanenko.[8] They showed the physical admissibility of a walking gait based on the ZMP evolution control. Li et al used the ZMP approach and proposed a learning control method to compensate the trunk perturbation for walking tasks.[17] Zheng et al, proposed a hierarchical control strategy of bipedal stability, by using a singular perturbation method induced by level terrain changing.[18] Kajita and Tani,[19] Gorce et al.,[1,20] developed a bipedal dynamic control method, based on the control of the center of mass acceleration of the biped. Taga et al., proposed a neuro-model which includes the dynamics of the human musculo-skeletal when performing the walking motion.[13]
   Considering kinematic gaits, some researchers deal with the bipedal trajectory evolution with joint coordination.[21] Jalics et al, examined a walking movement of a five-link biped where the input of the controller process is a set of fixed intermediate states.[22] They showed that a rhythmic movement can be achieved by determining a serie of walking states. The advantage of their approach is that the definition of the desired trajectory is very flexible and can be extended to execute some particular task. Channon, Beng and Hopkins, used a variational approach to generate optimal trajectories from a planar biped model walking over level ground.[23] They introduced simple cost function, that result in an optimal gait when minimized. The stepping motion was previously treated.[24] In this work, 2D model have been considered and the motion of the hip and knee joint is modelled using a cycloid velocity profiles.

However, concerning the specified task, the biped behavioural analysis facing an obstacle, and the relationship between the biped possibilities to execute the task, and the obstacle dimensions, remain a domain to develop. In this frame, we have to select suitable joints legs trajectories to execute the task. These trajectories must be chosen taking into account the biped and the obstacle dimensions, and must generate the required forward movements, maintaining the dynamic stability of the biped. So, the trajectories are selected so that the resulting gait satisfies some criteria (joint motion should be regular and should not exceed the biped joints limits. The feet in motion during the step, termed swing feet, should not hit the obstacle). The resulting joint trajectories will be used as input to a control system. Assuming that, this system can track the trajectories accurately, then the biped will step over the obstacle in an optimal manner.

In our study, we consider 3D bipedal model of the human body and a control/command architecture to ensure the

* Laboratoire de Génie Mécanique Productique et Biomécanique (LGMPB), 9 Avenue de la Division Leclerc, BP 140, 94234 CACHAN (FRANCE)
E-mail: philippe.gorce@iut-cachan.u-psud.fr.
** Laboratoire de physiologie du mouvement (LPM), ER CNRS 124, Université paris-sud, 91405 ORSAY cedex (FRANCE)

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dynamic stability of the biped during the execution task. This architecture has been previously developed by Gorce.[1] Then, termed kinematic analysis, we firstly propose an approach which control the stepping motion feasibility, based on a security notion definition. Secondly, we propose a trajectories generation process for this specific task. The purpose of our study is also, to combine robotic modelling with anthropometric and human control data, coming from a physiological experimental protocol.

This paper is organised as follows: In section 2, we briefly recall the control architecture used to ensure the dynamic stability of the biped. In section 3, we describe the experimental protocol. In section 4, we present the security notion and the "Admissible Control Domain" definition. In section 5, we detail the kinematic analysis and the trajectories generation process. Finally in section 6, we present some simulation results, and conclusions in section 7.

2. BIPED MODELLING AND CONTROL/ COMMAND ARCHITECTURE

Figure 1 illustrates a 11-link 3D biped.[1] This mechanical structure is composed of 11 links, with 12 joints pneumatically actuated (three for each leg representing hip, knee and ankle joints, two for each arm representing shoulder and elbow joints). This structure has been called "Bipman", acronym for "Biomechanical and pneumatic Man".

The control architecture that ensure the biped stability during the executing task, was previously developed by Gorce.[1,20,25,26] The method is based on a multi-chain systems control methodology developed in references 1 and 27. This one takes the "Bipman" robot I.D.M resolution into two legs and two arms I.D.M resolutions. The basic formulation is based on the recursive Newton-Euler formulation developed by Luh, Walker and Paul and modified Denavit-Hartenberg notation by Khalil Kleinfinger. This architecture can be represented as shown in Figure 2. The "Supervisor" level determines the general behaviour of the biped, according to the environment and to the specifications of the task to be performed.[26] The "Coordinator and limbs level", in which the global stability of the biped is ensured: the distributed forces and desired trajectories problems are solved, after the dynamic control of each leg and arm is performed.[25,28]

In this study, we deal only with the supervisor level, where we have to integrate the task behaviour analysis and the desired trajectories generation for the considered task.

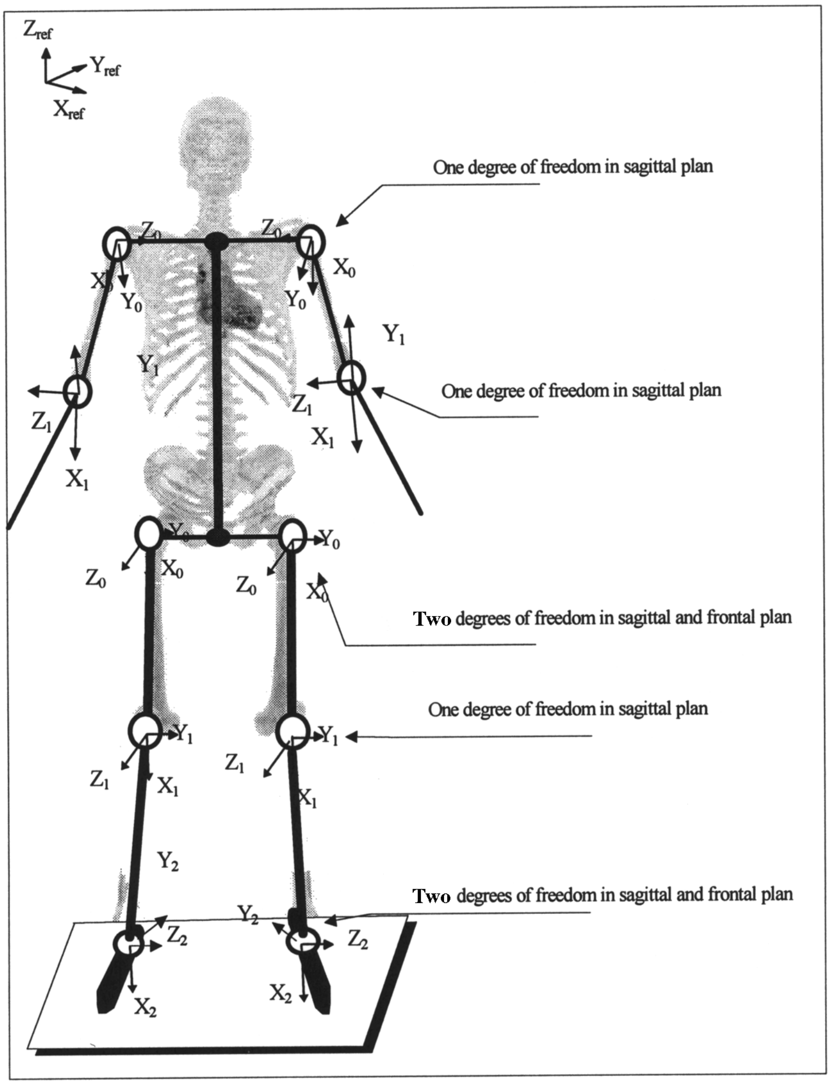

Fig. 1. Biped model.

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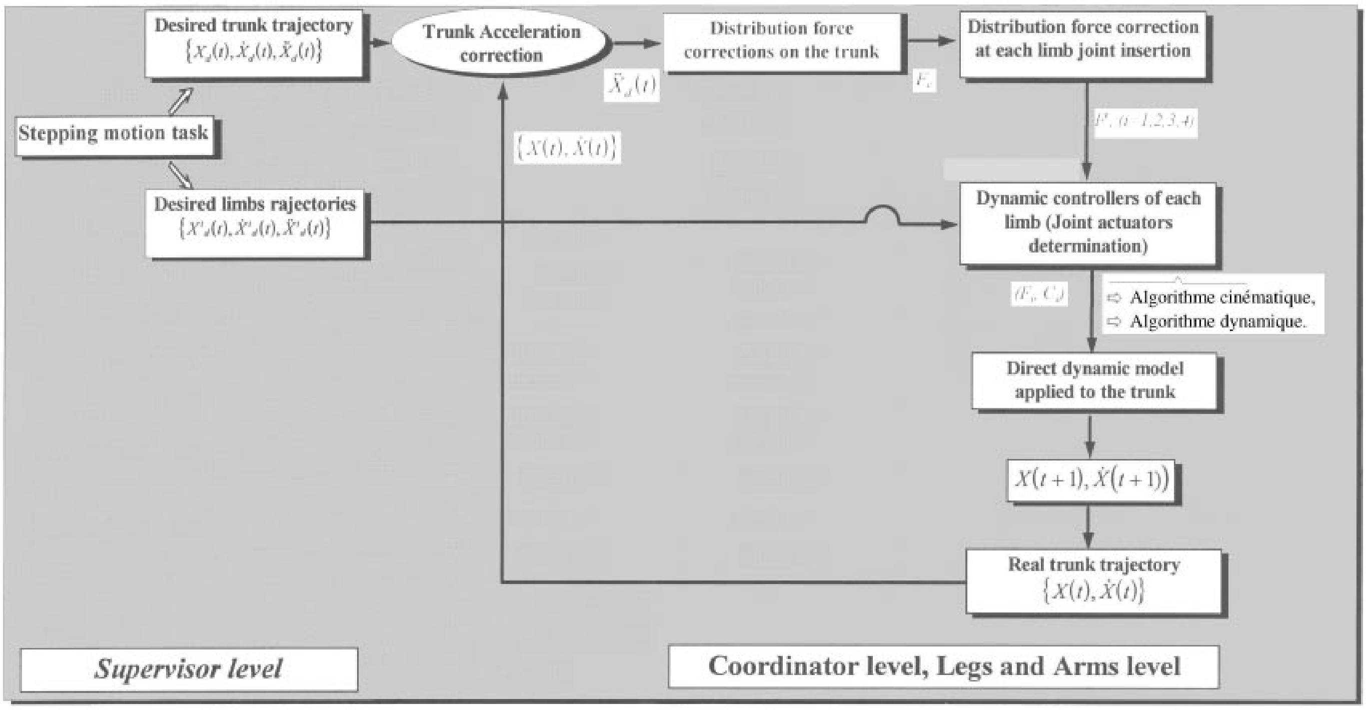

Fig. 2. Global view of control/command architecture.

3. EXPERIMENTAL PROCEDURE

We have used a VICON system motion analysis as shown in Figure 3. Three infrared cameras placed at 120 degree angle were used to measure the position of the light reflecting target placed on the legs and arms of the subject, after the (X-Y-Z) coordinates of the reference frame ($\Re_0$) were calibrated. Furthermore the ground reaction were obtained by using a force plate.

Initially the subject was in vertical standing posture, at variable distance (d) from an obstacle. Then he was asked to step ten times at a natural cadence. We have considered three subjects and three obstacles with different characteristics as shown in the Table I.

Only the trajectories information will be exploited in this study, the other data have been previously considered in the architecture.[29]

4. SETTING CONTROL FOR THE STEPPING MOTION

According to the experimental analysis,[29,30] the behaviour of the subject facing the obstacle, depends at first time, on the value of the distance (d) which validate or not the setting of

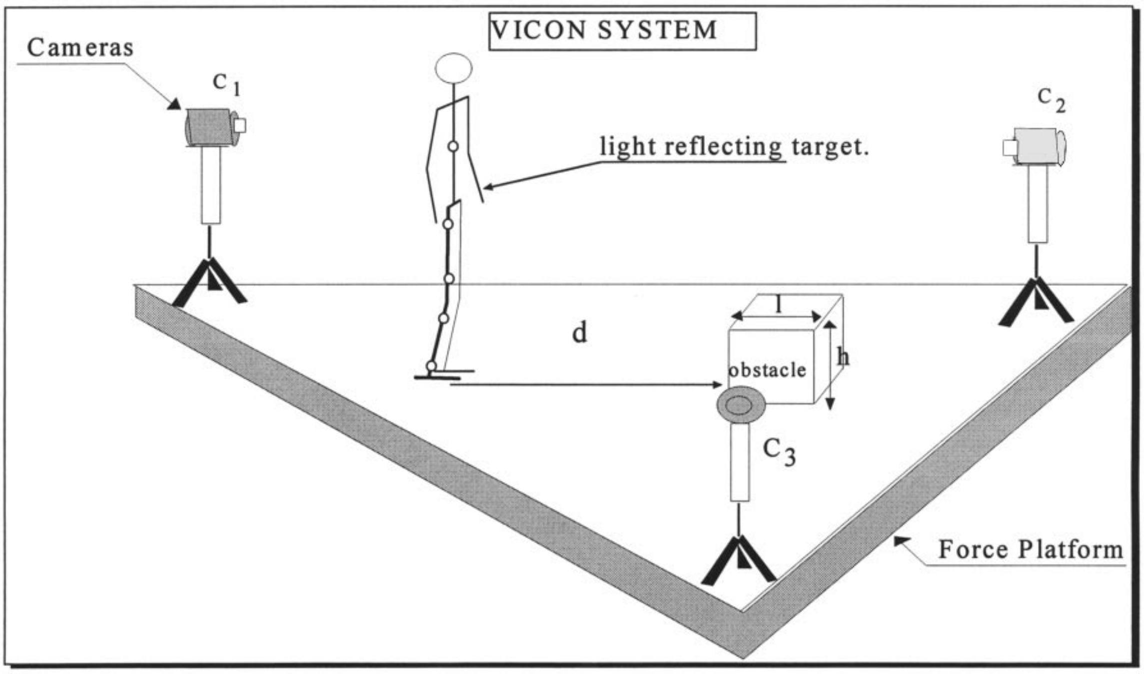

Fig. 3. Experimental system.

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the stepping motion. On this basis, we can introduce the following characteristic distances:

(i) $\boldsymbol{d_m}$: measured distance between the biped and the obstacle, $(d_m = d)$;
(ii) $\boldsymbol{d_I}$: Influence distance; if (d_m) converge to (d_I) then the biped became in interaction with the obstacle, consequently a decision will be taken to avoid a collision with the obstacle;
(iii) $\boldsymbol{d_s}$: Security distance; it represents the minimum distance between the biped and the obstacle. If the distance (d) is less than security distance, the stepping task will be impossible.

The previous definitions lead us to define a domain, called "***Admissible Control Domain***", that will control the setting of the stepping motion. This domain is noted "**D**" and is defined as follows:

$$D =]d_s, d_1[\qquad (1)$$

Thus, the expressions of the behavioural strategies for executing the stepping motion are:

Table I. Subjects and obstacles characteristics (experimental protocol).

Subjects		Obstacles	
Masse (Kg)	Height (m)	Height (m)	Width (m)
66	1.70	0.20	0.20
80	1.95	0.30	0.50
72	1.74	0.70	0.50

– **If** $\{d_m \in D\}$, then the stepping task is possible;

– **If** $\{d_m \notin D\}$, then two cases appear:

1 – **if** $\{d_m > d_1\}$, then the obstacle will be ignored and the biped can continue the current task (walk);

2 – **if** $\{d_m < d_s\}$, then the stepping task is impossible, the biped stops or takes another way.

The chosen distance to perform the task, called (d_c) is expressed as a function of the security distance and of the influence distance as follows:

$$d_c = d_s + \epsilon^*(d_I - d_2) \qquad ;\epsilon \in]0, 1[\quad . \qquad (2)$$

The subject behaviour facing the obstacle is shown in the Figure 4. The analytic computations of the characteristic distances are developed in section 5.

5. TRAJECTORY GENERATION FOR THE STEPPING MOTION

In classical approaches cycloid forms,[24] or a set of polynomial time functions[31] are chosen to describe the bipedal joint motion. In our study, we suppose that the joint motion at the hip and knee joints follow cycloid profiles. At a given instant during the stepping motion, the position of the biped can be specified using a coordinate vector (ϕ) given by:

$$\phi = [\psi, \theta^l_K, \theta^l_H, \theta^r_K, \theta^r_H] \qquad (3)$$

Here (ψ) represents the angle of the trunk to the vertical,

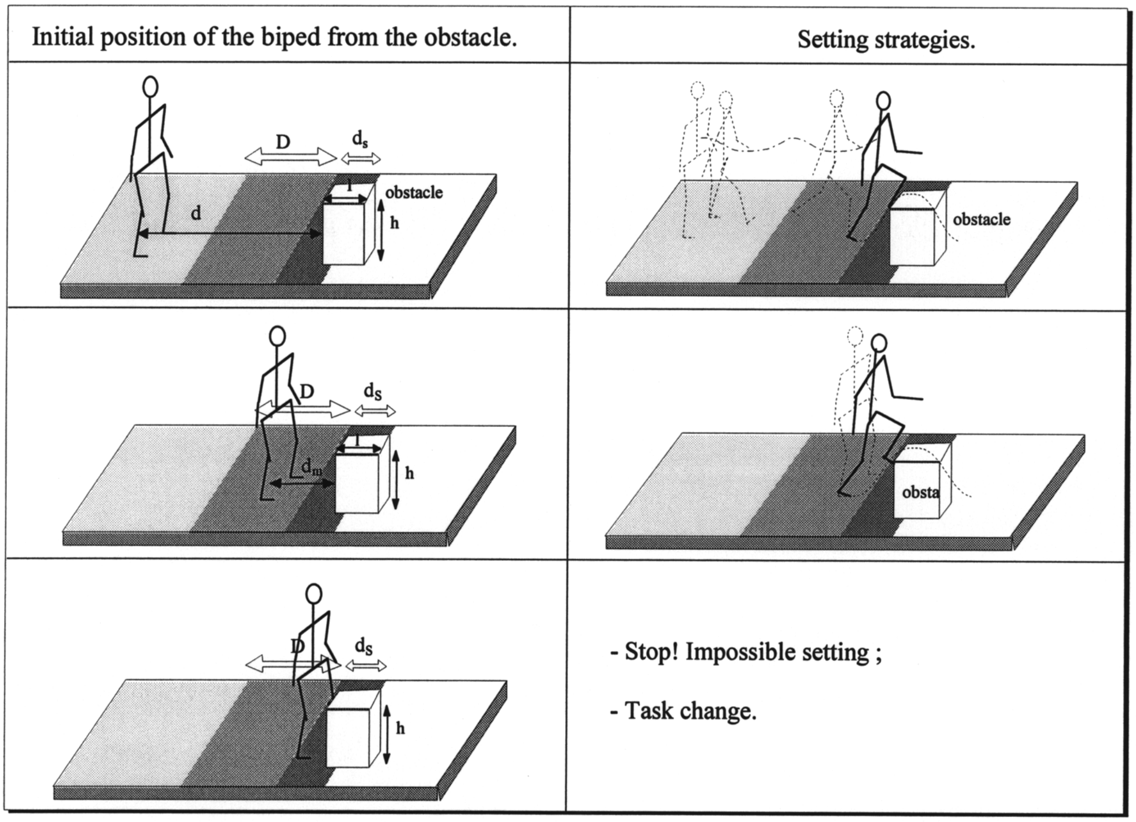

Fig. 4. Setting strategies of the stepping motion.

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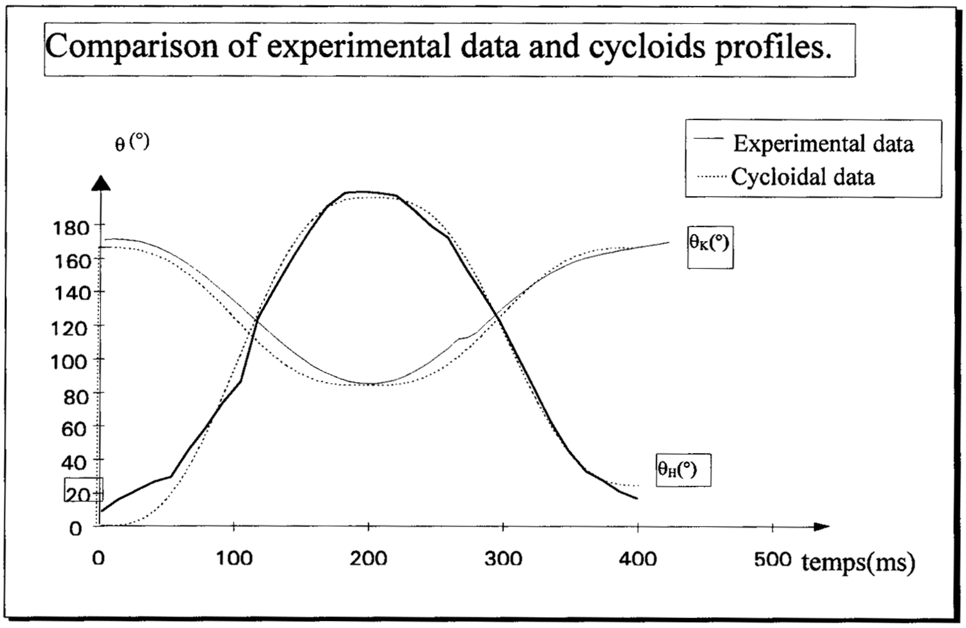

Fig. 5. Comparison of experimental and cycloid data.

(θ^l_K, θ^l_H) and (θ^r_K, θ^r_H) the angles of the hip and the knee joints, for the right (r) and left (l) legs. We suppose that the stepping task is performed by the right leg, followed by the left leg. During the step, we suppose that the trunk remain in the straight position, it means that the angle (ψ) is considered equal to zero. In a first analysis, the stepping motion, can be described in three stages:

stage 1: Double support, i.e. when the biped is on standing posture at time (t=0);
stage 2: Single support stage; it begins at time ($t=0^+$) with the swing foot leaving the ground. This stage ends at time ($t=T^-$);
stage 3: Impact stage; when the swing foot hits the ground at time (t=T).

The comparison of the experimental data with cycloid profiles is shown in the Figure 5.

5.1 Kinematic constraints

The chosen trajectories must satisfy some constraints called "Viability constraints" based on human behavioural, that will control the feasibility of the performed task. This constraint can be classified as follows:

(i) Joint motion should not exceed joint limits, this induces maximal and minimal values for the hip and knee angles (θ_H, θ_K) and the step length (L_p):

$$\theta_{H,\text{mini}} \leq \theta_H \leq \theta_{H,\text{maxi}}$$
$$\theta_{K,\text{mini}} \leq \theta_K \leq \theta_{K,\text{maxi}} \quad (4)$$
$$L_{P,\text{mini}} \leq L_P \leq L_{P,\text{maxi}}$$

(ii) The foot in motion during the step, called swing feet, should not hit the obstacle at any time t ($t \in [0^+, T^-]$).

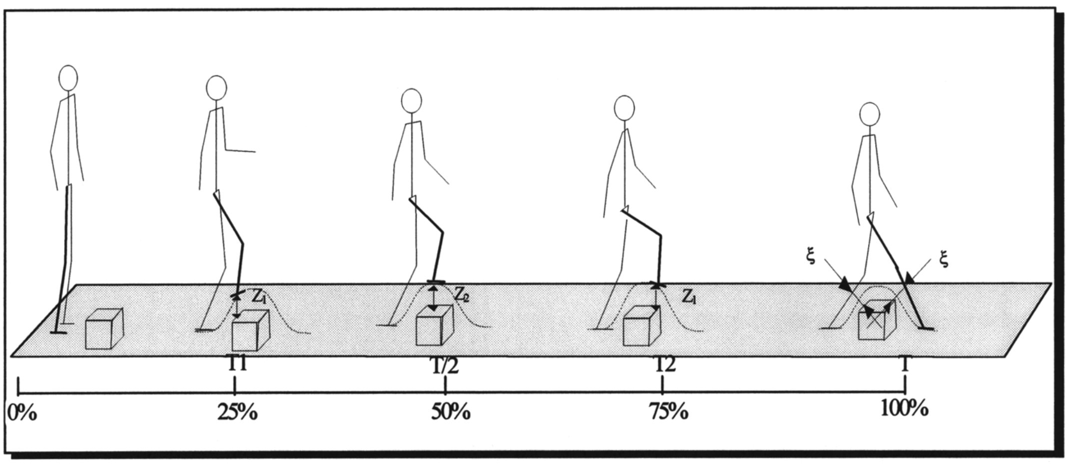

Fig. 6. Simulation of the legs motions during the stepping task.

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This means that the feet distance from the obstacle must be strictly positive during the stepping task ($z_1 > 0$, see Figure 6).

(iii) Referring back to the stepping stage definitions, the third stage results in the swing feet hitting the ground. This stage is assumed to be symmetrical, i.e. the legs are in symmetrical position from the obstacle. This assumption leads us to obtain the same leg distances from the obstacle, noted ξ in Figure 6. So we must verify that is ξ strictly positive.

These constraints allow us to compute the values raised by the hip and knee joints angles, at the (t_l, T/2, t_2, T) time. Their analytic expressions were obtained by respecting their dependence to the hip position in the reference frame. We obtain the following expressions:

$$\Rightarrow \theta_H(T) = \arcsin\left[\frac{\frac{l}{2} + d_c}{l_1 + l_2}\right] \tag{5}$$

$$\Rightarrow \theta_H(t1) = \arccos\left[\frac{z_H(t1) - (h + l1)}{l2}\right] + \psi_1 \tag{6}$$

$$\Rightarrow \theta_H(T/2) = \arccos\left[\frac{z_H(T/2) - (h + l1)}{l2}\right] + \psi_2 \tag{7}$$

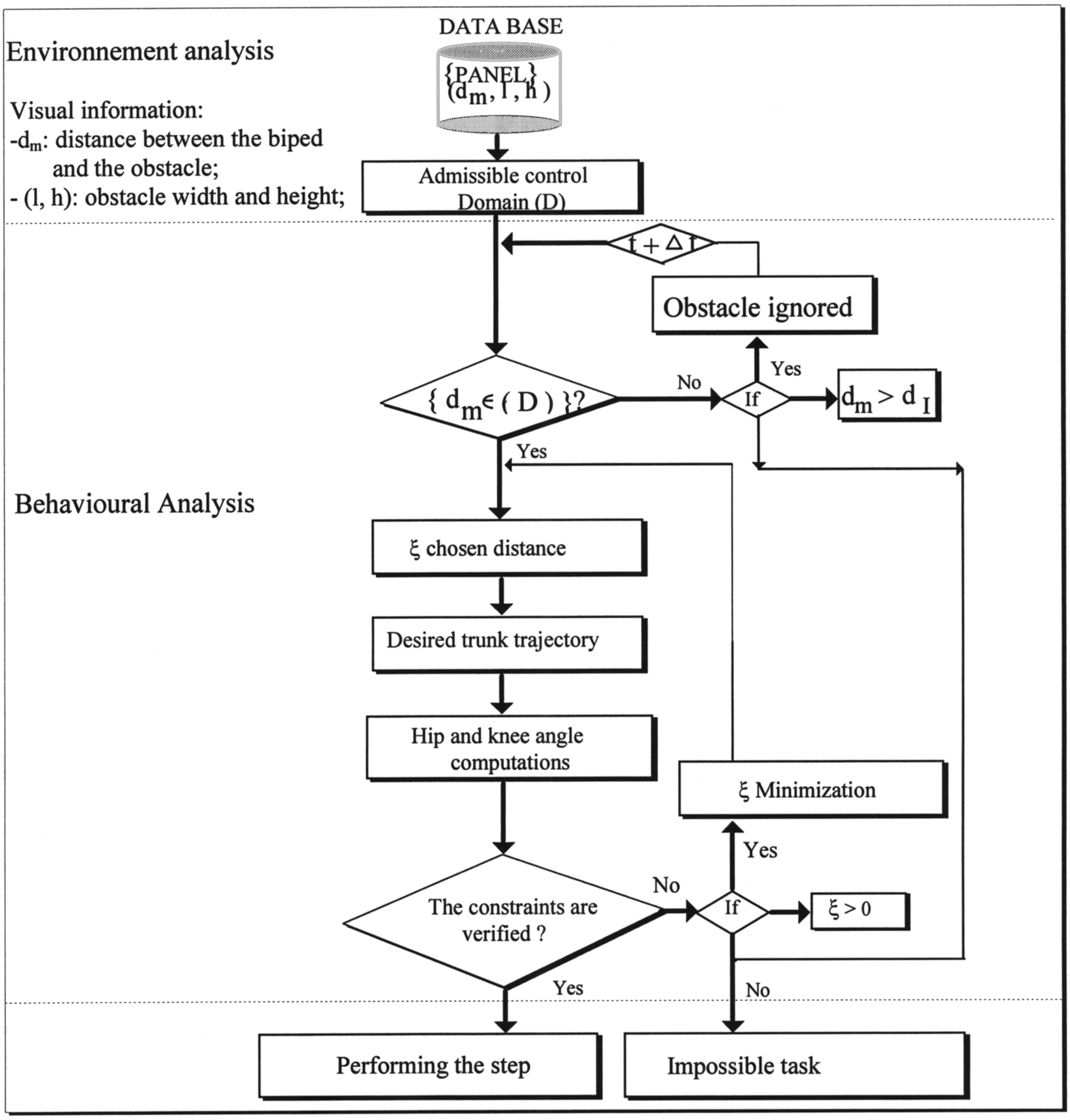

Fig. 7. Behavioural patterns and trajectory generation process for the stepping motion over an obstacle.

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with:

$$➪\ \psi_1 = \arccos\left[\frac{z_H(t1) - (h + l1 + Z1)}{l2}\right] - \arccos\left[\frac{z_H(t1) - (h + l1)}{l2}\right] \quad (8)$$

$$➪\ \psi_2 = \arccos\left[\frac{z_H(T/2) - (h + l1 + Z2)}{l2}\right] - \arccos\left[\frac{z_H(T/2) - (h + l1)}{l2}\right] \quad (9)$$

Finally, we build the hip joint motion, in the following form:

$➪\ t \in [0, t_1]$:

$$\theta_H = \frac{\theta_H(t_1)}{\pi}\left(\frac{\pi^* t}{t_1} - \sin\left(\frac{\pi^* t}{t_1}\right)\right) \quad (10)$$

$➪\ t \in \left]t_1, \frac{T}{2}\right]$:

$$\theta_H = \frac{\theta_H(T/2) - \theta_H(t_1)}{\pi}\left(\pi^* \frac{t - t_1}{\frac{T}{2} - t} - \sin\left(\frac{t - t_1}{\frac{T}{2} - t}\right)\right) + \theta_H(t_1) \quad (11)$$

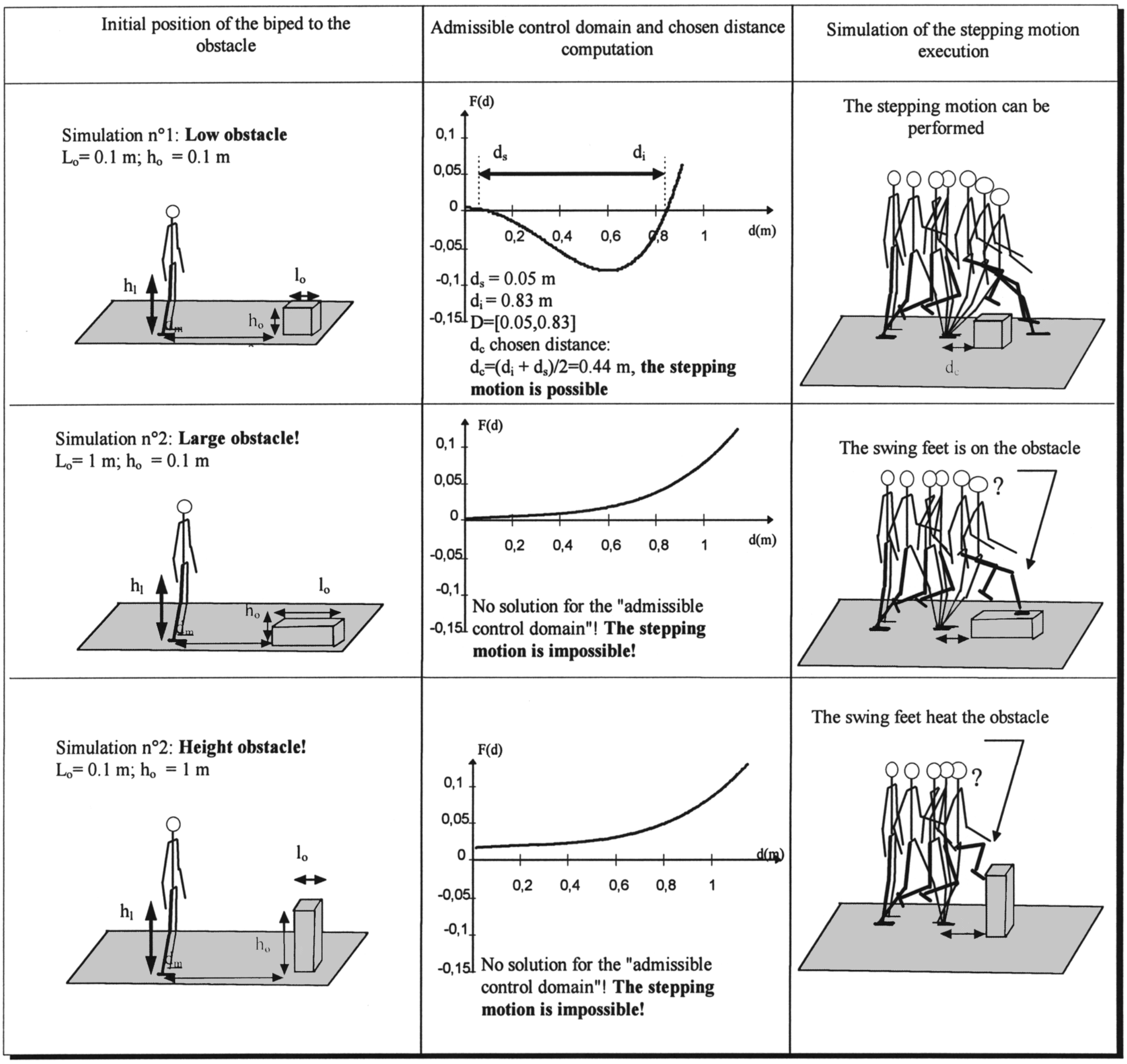

Fig. 8. Simulation results (Security notion, influence of the object dimensions on the stepping feasibility).

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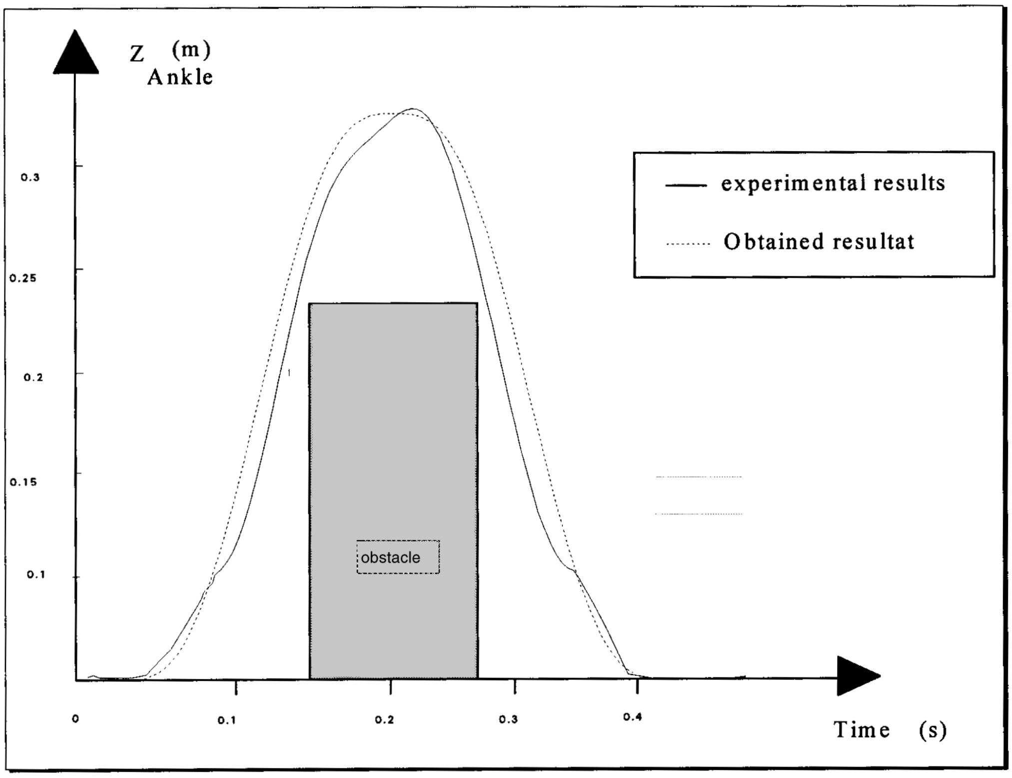

Fig. 9. Comparison of experimental and computational vertical swing feet trajectory.

➪ $t \in \left]\frac{T}{2}, t_2,\right]$:

$$\theta_H = \frac{\theta_H(t_1) - \theta_H\left(\frac{T}{2}\right)}{\pi}\left(\pi^*\left(\frac{t-\frac{T}{2}}{t_2-\frac{T}{2}}\right) + \sin\left(\frac{t-\frac{T}{2}}{t_2-\frac{T}{2}}\right)\right) + \theta_H\left(\frac{T}{2}\right) \quad (12)$$

➪ $t \in]t_2, T]$:

$$\theta_H = \frac{\theta_H\left(\frac{T}{2}\right) - \theta_H(t_1)}{\pi}\left(\pi^*\left(\frac{t-t_2}{T-t_2}\right) + \sin\left(\frac{t-t_2}{T-t_2}\right)\right) + \theta_H(t_1) \quad (13)$$

Where:

- (l_1, l_2) = Lower and upper leg segment length;
- (l, h) = Obstacle Width and height;
- (L_p, T) = Step length and duration;
- $z_H(t_1)$ = Vertical hip joint position, at time t_1 (respectively at the t_2 and T/2 instants).

With a similar method we build the knee joint motion. The feet trajectories are expressed as a function of the joints motion at the hip and knee joints. The two vertical and horizontal feet motions are of the following form:

$$➪ x_p = x_H + l_2{}^*\sin(\theta_H) - l_1{}^*\sin(\theta_H + \theta_G) \quad (14)$$

$$➪ Z_p = Z_H - l_2{}^*\cos(\theta_H) + l_1{}^*\cos(\theta_H + \theta_G) \quad (15)$$

5.2 Behavioural patterns and trajectory generation process

The retained optimal strategies to perform the stepping motion, is based on the ξ distance control. Furthermore, this parameter appears as a function of the kinematic parameters of the biped. So, by controlling the ξ value we validate or not the possibility of the stepping motion, and ensure the task without hitting the obstacle during the step. The Figure 7 displays different steps of the “Behavioural Patterns And Trajectory Generation” process.

The expressions obtained concerning the characteristic distances are:

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$$\Rightarrow d_S = (l1 + l2) \times \sin\left[arctg\left(\frac{\frac{l}{2}}{z_H(T) - h} \right) \right] - \frac{l}{2} \quad (16)$$

$$\Rightarrow L_p = 2 \times (l1 + l2) \times \sin(\theta_H(T)) \quad (17)$$

$$\Rightarrow d_l = d_S + L_{p,\max} \quad (18)$$

$$\Rightarrow \xi = \frac{\left(\frac{l}{2}\right)}{\sin\left[arctg\left(\frac{\left(\frac{l}{2}\right)}{z_H(T) - h} \right) \right]} \times \sin\left[\theta_H(T) - arctg\left(\frac{\left(\frac{l}{2}\right)}{z_H(T) - h} \right) \right] \quad (19)$$

where :

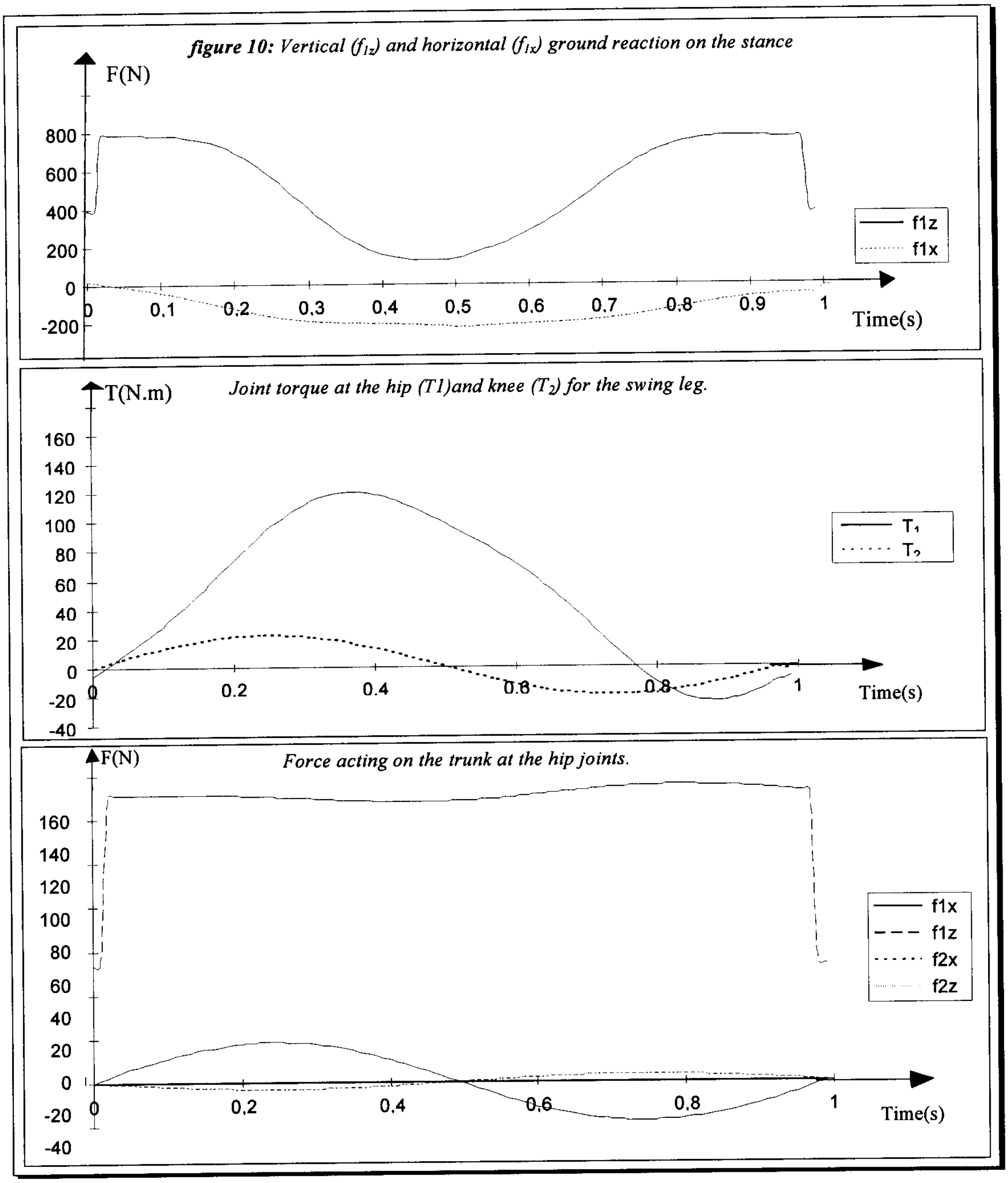

Fig. 10. Simulations results.

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– d_c = Chosen distance;

– (d_I, d_S) = Influence distance and Security distance;

– (L_p, T) = Step length and duration. $L_{p,max}$ the maximal step length.

Furthermore, we have introduced a geometrical function, that allows us to compute directly the security and influence distances providing the bounds of the admissible control domain. This function is constructed in such a way that positive values correspond to the collision of the legs with the obstacle and negative values correspond to valid configuration of the stepping motion. The Figure 8, presents three different simulations based on the Admissible control domain definition.

6. RESULTS AND DISCUSSION

Referring back to the control architecture (Figure 2), the behavioural approach developed before is introduced at the "supervisor" level. So according to the information about the obstacle (visual information), this level gives the desired center of mass position and joint position for each leg. Then the coordinator level analyses those informations to compute the induced joints torque. This was implemented on a PC-Pentium computer developed in language *C*. At each time step, the coordinator level compute the joint torque at the hip and knee joints that will ensure the trajectories tracking.

Figure 9 shows the correlation of the swing feet trajectory with experimental data. The Figure 10 gives the simulations results obtained for the stepping motion over an obstacle of 20 cm high and 25 cm wide. It shows the ground reaction on the stance feet, the forces and torque joints developed at the joints, where:

– (f_{1x}, f_{1y}): vertical and horizontal ground reaction on the stance feet;
– (t_{1x}, t_2): torque joints at the hip and knee joints of the swing leg;
– (f_{1x}, f_{1z}): horizontal and vertical forces exerted by the stance leg on the trunk, at the hip joint;
– (t_{1x}, t_2): horizontal and vertical forces exerted by the swing leg on the trunk, at the hip joint.

7. CONCLUSION

In this study, we have proposed a new approach to solve the bipedal stepping motion feasibility and the trajectories generation. For that, we have introduced a security notion that will validate or not the task feasibility. This has led us to define an "Admissible Control Domain" for the task execution, then we have developed behavioural patterns and a trajectory generation process for the stepping motion task. This procedure comes to consider the possibilities of stepping over the obstacle in optimal conditions, or of avoiding it by stopping or taking another way. We base our study on a control/command architectured to ensure the dynamic stability during the task execution. Future works will focus on a global "Admissible Control Space" definition taking into account the (d, l, h) parameters.

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