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A new approach to dynamic posture control

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SUMMARY

In this paper, we propose an approach which ensures the dynamic stability of a biped robot called "BIPMAN". It is based on the correction of the trunk center of mass acceleration and on the distribution of the forces exerted by the limbs on the trunk. This latter is performed by means of a linear programming method (the simplex method). The retained criterion allows to optimize force distribution as well as trunk roll and pitch angles. Weighting factors are introduced into this criterion in order to define criteria adapted to specific tasks. Modifying these factors is a solution to the task transition problem. Many simulation results are presented to demonstrate criteria and constraints influences on dynamic stability. They lead us to introduce a new approach called *RTCA* (*R*eal *T*ime *C*riteria and *C*onstraints *A*daptation). This relies on the analysis of position, velocity and acceleration vectors for criterion real time adaptation and on forces analysis for constraints real time adaptation. The *RTCA* approach is finally validated through simulations results for a specific task.

KEYWORDS: Postural control; Biped robot; Simplex method; *RTCA* approach.

1. INTRODUCTION

In the robotic field as well as in the biomechanic field, optimization methods are now currently used. Indeed, in the robotic field the solution of the force distribution in multi-chains mechanisms is not unique and involves the solution of an optimization problem. Several algorithms have been proposed which use different techniques based on: the pseudo-inverse method,[1] the linear programming method (Simplex),[2,3] and the non linear programming method based on Lagrange multipliers[4] or Compact-dual method.[5] In the biomechanic field, kinematic redundancies as well as muscular redundancies suggest that human movements are solutions of optimization problems. Actually, most movements are performed with some purpose in mind such as to stand without falling, to pick up an object or to set one's gaze in a certain direction. In this way, two kinds of optimization criteria and constraints have been used to study human movement:[6] "effort related" criteria such as the minimization of tissue stresses,[7,8] or the minimization of the energy storage,[9] or "task related" criteria such as movement time and position error minimization, scaling of the amplitude or the speed of the reference trajectory, jerk minimization, additional neuromuscular penalty.[10] Seif Naraghi[10] and Yamaguchi[11] used a combination of these two kinds of criteria. The optimization methods often used are gradient-based which do not guarantee conversion to a solution, random search, or hybrid methods which attempt to incorporate the best of each approach.

The optimization criterion and constraints generally used for real-time control of complex mechanisms are fixed all over the control duration. This is perfect in an ideal situation, when a unique task is performed under a weak perturbation. However, when a strong perturbation or a transition from a task to another one occurs, the control strategy must be well adapted to prevent a biped fall and to insure an automous evolution from one task to another one. Fall is not acceptable because of damages it involves to the biped structure and more generally to embedded systems. Moreover, no solution has been proposed concerning the autonomous task transition problem.

On the basis of the human dynamic behaviour in response to external perturbations, we propose a real-time adaptation of the criterion and the constraints in order to improve the solution of the force distribution problem. Many methods are computationally inefficient and cannot be used for real-time applications. Moreover, the optimization method used must take into account real-time and materials constraints which are imposed by all embedded systems (available computation capacity, energy consumption, dimensions, weight . . .). We therefore propose a control strategy based on the simplex method which realizes a compromise between modelization complexity and computation time.[3]

In this way, we propose to show how the force distribution problem applied to a biped is solved with respect to different task conditions, and we develop a *R*eal *T*ime *C*riteria and constraints *A*daptation approach called *RTCA*. The general criterion retained allows one to minimize the bulk and the weight due to the actuators and to the related systems and to minimize parameters related to stability such as trunk roll and pitch angles.

The purpose of our study is also to contribute to a better understanding of the dynamic behaviour of a standing man facing specific tasks. More generally, we look for "optimal" strategies adapted to body motion under perturbation effects. In this way, we aim at determining the optimal distribution of the forces

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exerted by the limbs on the trunk of a biped structure with respect to a specified task.[12,13] This mechanical structure is composed of 11 links with 12 joints pneumatically actuated and has been called "*BIPMAN*", acronym for "*BI*omechanical and *P*neumatic *MAN*" (Figure 1).

This paper is organized as follows: In section 2 we briefly recall the overall control architecture and especially the mathematical formulation of the optimization problem. In section 3, we present the results of simulations with respect to different optimization criteria and constraints. According to these results, the *RTCA* approach is illustrated in section 4 for biped dynamic stability under external perturbations.

2. CONTROL/COMMAND ARCHITECTURE

The control architecture is composed of three levels: The upper level, called the "*Supervisor*" level determines the general behaviour of the biped, according to the environment and to the specifities of the task to be performed. The intermediate level is the "*Coordinator*" in which the global stability of the "*BIPMAN*" robot is ensured: the distributed forces and desired trajectories problems are solved. The lower level is the "*Limbs*" level in which the dynamic control of each leg and arm is realized.

The method is based on the multi-chain systems control methodology developed in references 2 and 3. This one tackles the "*BIPMAN*" robot I.D.M. (Inverse Dynamic Model) resolution into two stages:[12]

—first the biped is considered as a set of four subsets. Each subset is composed by a leg or an arm. At this stage this allows to break down 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[14] and the modified Denavit-Hartenberg notation developed by Khalil-Kleinfinger.[15]

—afterwards, the legs or the arms are no longer independent but really connected together by the trunk and the ground. In order to obtain the desired motion of the biped, the leg movement is coordinated and a trajectory pattern for the tip of the legs (feet) is defined. Furthermore, to compensate for the fact that we do not take into account the interaction phenomena in the legs I.D.M. resolution, we ensure the robot equilibrium by controlling the trunk stability.

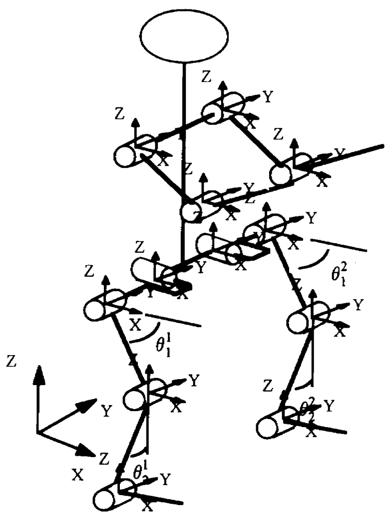

Fig. 1. *BIPMAN.*

A global view of this architecture can be illustrated as follows (Figure 2).

To correct the trunk acceleration, we apply the Dynamic Fundamental Principle on its center of mass with respect to a reference frame (R_0) attached to this point. So, we obtain the following equation:

$$\begin{bmatrix} m_0 & 0 \\ 0 & {}^0I_0 \end{bmatrix} \cdot \begin{bmatrix} {}^0a_{c0} \\ {}^0\dot{\omega}_{c0} \end{bmatrix} + \begin{bmatrix} -m_0 \cdot {}^0g \\ {}^0\omega_{c0} \times ({}^0I_0 \cdot {}^0\omega_{c0}) \end{bmatrix} = \begin{bmatrix} \sum_{k=1}^{4} F_k \\ \sum_{k=1}^{4} M_k \end{bmatrix} \quad (1)$$

where

—m_0 is the trunk mass;
—J_3 is the 3×3 identity matrix;
—${}^0I_0$ is the trunk inertia matrix;
—${}^0a_{c0}({}^0\dot{\omega}_{c0})$ is the trunk absolute (angular) acceleration;
—${}^0g$ is the gravitational vector;
—${}^0\omega_{c0}$ is the trunk angular velocity;
—$F_k(M_k)$ is the resultant force (moment) applied to the trunk by the k^{th} limb.

A reduced form of the equation (1) can be written as follows:

$$A \cdot \ddot{X} + B = F \quad (2)$$

If at time instant t, $X_d(t)$ represents the desired trunk center of mass trajectory and $X(t)$ the real trajectory of this one, it is possible to effect the following correction of the acceleration at the next time step, referred to as $t+1$:

$$\ddot{X}(t+1) = \ddot{X}_d(t+1) + K_v \cdot (\dot{X}_d(t+1) - \dot{X}(t)) + K_p \cdot (X_d(t+1) - X(t)) \quad (3)$$

where

—$\ddot{X}(t+1)$ represents the desired trunk center of mass acceleration at $t+1$ time;
—K_p and $K_v \in \Re^{6\times 6}$ represent constant matrices which guarantee asymptotic stability.

To correct the desired limbs accelerations, we use the equation of transformation of the accelerations. This one shows that the limbs are attached to the trunk:

$${}^0a_0^k(t+1) = {}^0a_{c0}(t+1) + {}^0\dot{\omega}_{c0}(t+1) \times {}^0r_{c0,0}^k + {}^0\omega_{co}^d(t+1) \times ({}^0\omega_{c0}^d(t+1) \times {}^0r_{c0,0}^k) \quad (4)$$

with

$$\ddot{X}(t+1) = \begin{bmatrix} {}^0a_{c0}(t+1) \\ {}^0\dot{\omega}_{c0}(t+1) \end{bmatrix}, \quad (5)$$

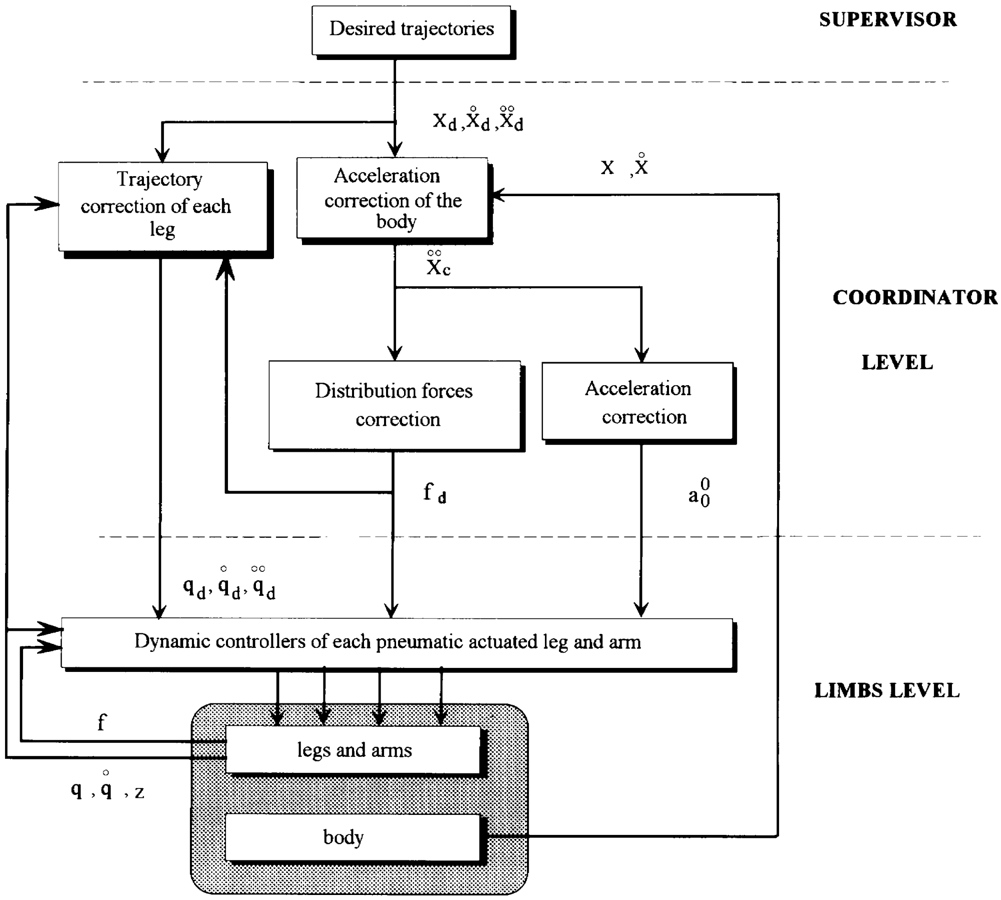

Fig. 2. Global view of "*BIPMAN*" architecture.

${}^{0}a_0^k$ is the acceleration of the connection point between the k^{th} limb and the trunk

${}^{0}r_{c0,0}^k$ is the position vector between the trunk center of mass and the connection point of the k^{th} limb

According to equation (2), if at time instant $t+1$ we apply the desired trunk center of mass acceleration $\ddot{X}(t+1)$, the total limbs/body interaction force must become:

$$F(t+1) = A \cdot \ddot{X}(t+1) + B \tag{6}$$

So it is necessary to well distribute this correction over the limbs in an order to obtain at time instant $t+1$ a limbs/trunk interaction force equal to $F(t+1)$. But as the trunk is loaded by several limbs there are more than one solution. However, using an optimization algorithm based on the simplex method, it is possible to find one particular solution which tends to minimize an objective function. As this solution depends on time instant, it is a local one. Then to correct the limb force distribution, we solve the following problem:

$$\textit{Minimize } [\Phi] = [D] \cdot [F] \tag{7}$$

$$\textit{with } [K] \cdot [F] = [E] \tag{8}$$

$$\textit{and } [H] \cdot [F] \leq [L] \tag{9}$$

where:

$[\Phi]$: is the objective function $[1 \times 1]$,
$[D]$: is the cost vector of the objective function $[1 \times 6]$,
$[F]$: is the forces/moments vector $[24 \times 1]$,
$[K]$: equality constraints matrix $[1_e \times 24]$,
$[E]$: equality constraints vector $[1_e \times 1]$,
$[H]$: inequality constraints matrix $[1_i \times 24]$,
$[L]$: inequality constraints vector $[1_i \times 1]$,
1_i: inequality constraints number,
1_e: equality constraints number,

The purpose of the next section is to define the $[D]$, $[K]$ and $[H]$ matrices and to show how modifications of these matrices change the solution $[F]$ to the force distribution problem associated with the maintaining of an erect stance when the biped is submitted to an external perturbation.

3. SIMULATION RESULTS

In this section we describe simulation results obtained with different criteria and constraints for a simple perturbation around the biped standing posture.

3.1 Simulation principle

The desired trunk and limbs trajectory are known. If the real trunk trajectory is assumed to be equal to the

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desired trajectory the algorithm calculates a force distribution which corresponds to the biped static equilibrium in a standing posture. Then an initial trunk trajectory error is introduced which initiates the correction process. Once the desired trunk acceleration $\ddot{X}(t+1)$ has been calculated, $\dot{X}(t+1)$ and $X(t+1)$ are then calculated through numerical integration using motion equation (2). As our purpose is not the precision of this numerical integration, a first order Euler integration algorithm is used. The errors $|X_d(t+1) - X(t+1)|$ and $|\dot{X}_d(t+1) - \dot{X}(t+1)|$ are calculated. We assume that convergence is ensured when these two errors are less than 10^{-6} during several integration steps.

3.2 Constraints definition

The constraints have been decomposed into "geometric" and "dynamic" constraints.

3.2.1 **Geometric constraints.** First of all, an obvious geometric constraint is due to the fact that the feet touch the ground all over the simulation. This induces a maximal vertical value for the trunk center of gravity position which must not be exceeded during simulation (see Figure 3). Thus:

$$z_G(t) \leq z_{G\,\max} \tag{10}$$

In fact, this means that the real trunk trajectory along the vertical axis must asymptotically converge on the desired trunk vertical trajectory. Moreover, the angular perturbation cannot be imposed at random but must also satisfy this constraint.

Since it is not possible to produce ankle torques without feet, another geometric constraint is related to the feet lengths. In other words, the feet must be long enough so that the ground reaction application point (also called Zero Moment Point) is within the feet support area. The following constraints are therefore taken into account:

$$L_h \leq X_P \leq L_t \quad \text{and} \quad -l \leq Y_P \leq +l$$

where X_p and Y_p are, respectively, the antero-posterior and lateral positions of the Zero Moment Point with respect to the ankles axis. L_h and L_t are, respectively, the distance from heel to ankle axis and from angle axis to toes (see Figure 3).

3.2.2 **Dynamic constraints.** In the method described above, the legs and the arms seem to play the same part. However, in the erect stance the legs have a supporting role that the arms have not. Moreover, the arms motion can be considered as a perturbation to the trunk equilibrium.[16–18] In this way, as the arms motions are known, the forces/moments imposed by the trunk to the arms to insure these motions are also known. So they must be imposed as equality constraints in the optimization problem. They are written as follows:

$$F_3 = F_{ra}(t+1), \quad M_3 = M_{ra}(t+1) \tag{11}$$

$$F_4 = F_{la}(t+1), \quad M_4 = M_{la}(t+1) \tag{12}$$

where:

—F_3/M_3 are the right arm force/moment vectors $[3 \times 1]$,
—F_4/M_4 are the left arm force/moment vectors $[3 \times 1]$,
—F_{ra}/M_{ra} are the force/moment vectors corresponding to the right arm desired motion $[3 \times 1]$,
—F_{la}/M_{la} are the force/moment vectors corresponding to the left arm desired motion $[3 \times 1]$.

So, we define a set of "basic constraints" which are essential to find a solution to the distribution force problem. They are imposed whatever the critierion is. This set is as follows:

$$\begin{aligned}
&\sum_{k=1}^{4} F_k = F_c(t+1) \\
&\sum_{k=1}^{4} M_k = M_c(t+1) \\
&F_3 = F_{ra}(t+1), \quad M_3 = M_{ra}(t+1) \\
&F_4 = F_{la}(t+1), \quad M_4 = M_{la}(t+1) \\
&F_{z_k} \geq \min \quad \text{and} \quad F_{z_k} \leq \max 1 \quad \text{for} \quad k = 1, 2
\end{aligned} \tag{19}$$

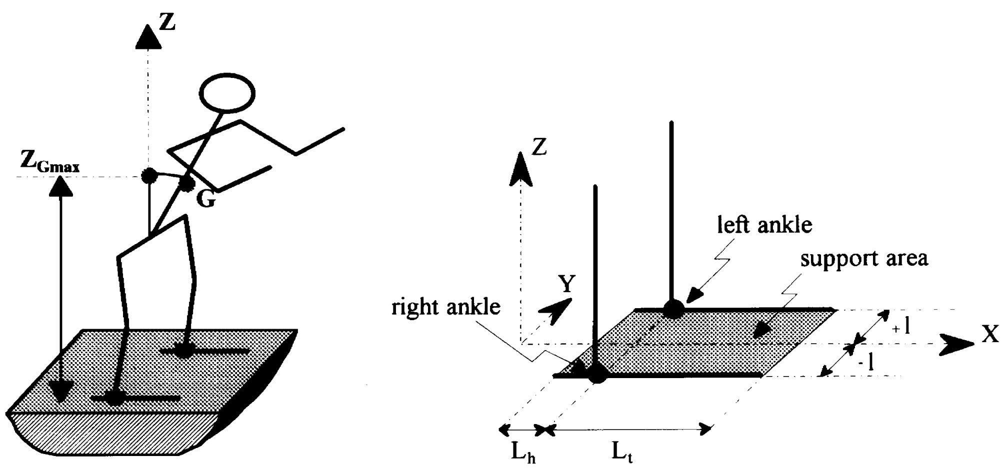

Fig. 3. Geometric constraints.

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where

—F_{z_k} is the vertical component of F_k,
—the different values of k correspond to:

1 = right leg 2 = left leg

3 = right arm 4 = left arm

The first two equalities correspond to total limbs/trunk force/moment interaction. The following two are related to arms motions. The first inequalities impose that the legs support continuously the trunk. The object of the other inequalities is to eliminate the solutions for which the vertical forces are too big.

The solutions of the force distribution problem are the forces/moments $[F]$ exerted by the limbs on the trunk. Thus all the constraints of the optimization must be related to these variables $[F]$. However, common sense and previous studies[19–21] suggest that friction and sliding constraints on the forces exerted by the feet on the ground are likely to exist. So, the non-sliding constraint defined by the Coulomb law is introduced:

$$\mu^2 \cdot f_{z_i}^2 \geq f_{x_i}^2 + f_{y_i}^2 \tag{13}$$

where:

—μ is the friction coefficient depending on the ground properties,
—f_{z_i} is the normal component of the force f exerted by the i^{th} foot on the ground,
—f_{x_i} et f_{yi} are tangential components of the force f exerted by the i^{th} foot on the ground.

Thus a solution $[F]$ which satisfies the optimization criterion and the constraints may lead to unacceptable feet/ground forces f. To circumvent this drawback an additional constraints on $[F]$ must be added.

3.3 Criteria

To correct the leg and arm force distribution, we use the following general criterion:

$$Minimize:\ a_1F_{z1} + a_2F_{z2} + a_3F_{z3} + a_4F_{z4} \tag{14}$$

where a_i are weighting factors. By modifying an *ai* value, it is possible to make the corresponding *Fzi* variable more significant. This will be done according to behavioural rules directly infered from biomechanical studies. This general criterion not only allows one to optimize the force distribution but also indirectly insures the stability by minimizing roll and pitch angles.

In a first step, we have retained the three following criteria corresponding to a_i values equal to 1 or −1.

$$Minimize:\ F_{z1} + F_{z2} + F_{z3} + F_{z4} \tag{15}$$

This criterion corresponds to minimization of the total vertical force applied to the trunk by the limbs. It may be used to indicate that the efforts are minimal in common posture.

$$Minimize:\ (F_{z1} + F_{z3}) - (F_{z2} + F_{z4}) \tag{16}$$

$$Minimize:\ (F_{z2} + F_{z4}) - (F_{z1} + F_{z3}) \tag{17}$$

These criteria correspond to the minimization of the differences between the vertical forces applied to the trunk respectively by the right leg and arm and the left leg and arm. The actual criterion which minimizes the trunk roll angle is:

$$Minimize:\ |(F_{z1} + F_{z3}) - (F_{z2} + F_{z4})| \tag{18}$$

However, the simplex method involves only linear criteria and constraints. Thus this criterion has been replaced by the two linear criteria (16) and (17). They have already been used in references 12 and 22.

3.4 Results

Initially, the biped is in a vertical standing posture. Because of an external perturbation, the biped trunk is suddenly forward tilted from 5° to 20°. Our purpose is to determine a solution $[F]$ which insures the trunk stability in vertical position under different constraints.

3.4.1 **Criteria influence.** Figure 4 displays the solution provided according to the three proposed criteria.

The first obvious remark is that the third criterion does not provide a solution. Many reasons could explain this. The chosen K_p and K_v could lead to a limit solution which cannot be reached with the third criterion for numerical reasons. As the basic constraints are the same for F_{z1} and F_{z2} (same weighting factors), this could prevent the simplex algorithm from finding a solution because of a bad choice between F_{z1} and F_{z2}. For example, in order to find a solution the algorithm should choose F_{z2}, but actually chooses F_{z1} which is the first of the two variables. This is not acceptable for real-time control of our biped because this could lead to its fall. This means that this criterion which may be useful in other circumstances is not adapted to the perturbation imposed.

The first two criteria lead to two different support conditions. Indeed, the first criterion leads to a bilateral support solution, while the second one leads to an almost unilateral support. This means that the first criterion is probably more appropriate for maintening the standing posture, while the second one could be used in transition phase between the standing posture and the first step of the gait. In this way, when successive tasks must be performed, the optimization criterion must be changed. For example, when gait follows a standing phase the criterion may be switched from (15) to (16) to insure the transition phase from bipedal to unilateral support.

3.4.2 **Constraints influence.** Figure 5 presents the simulation results for a 20° forward rotation of the trunk with

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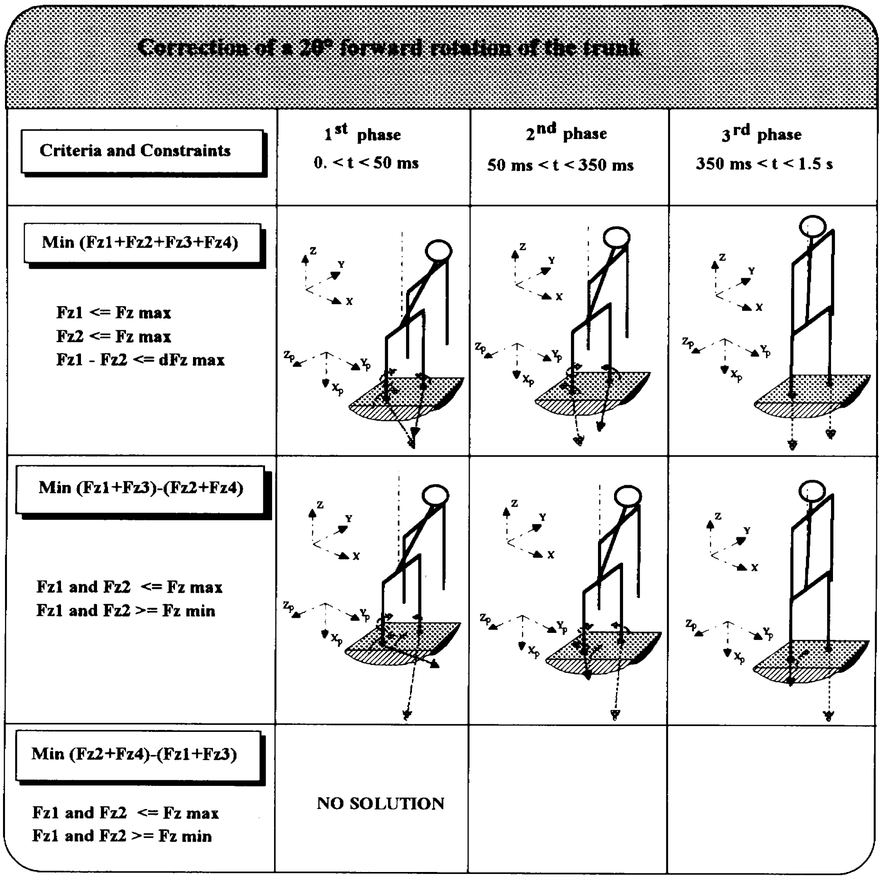

Fig. 4. Criteria influence.

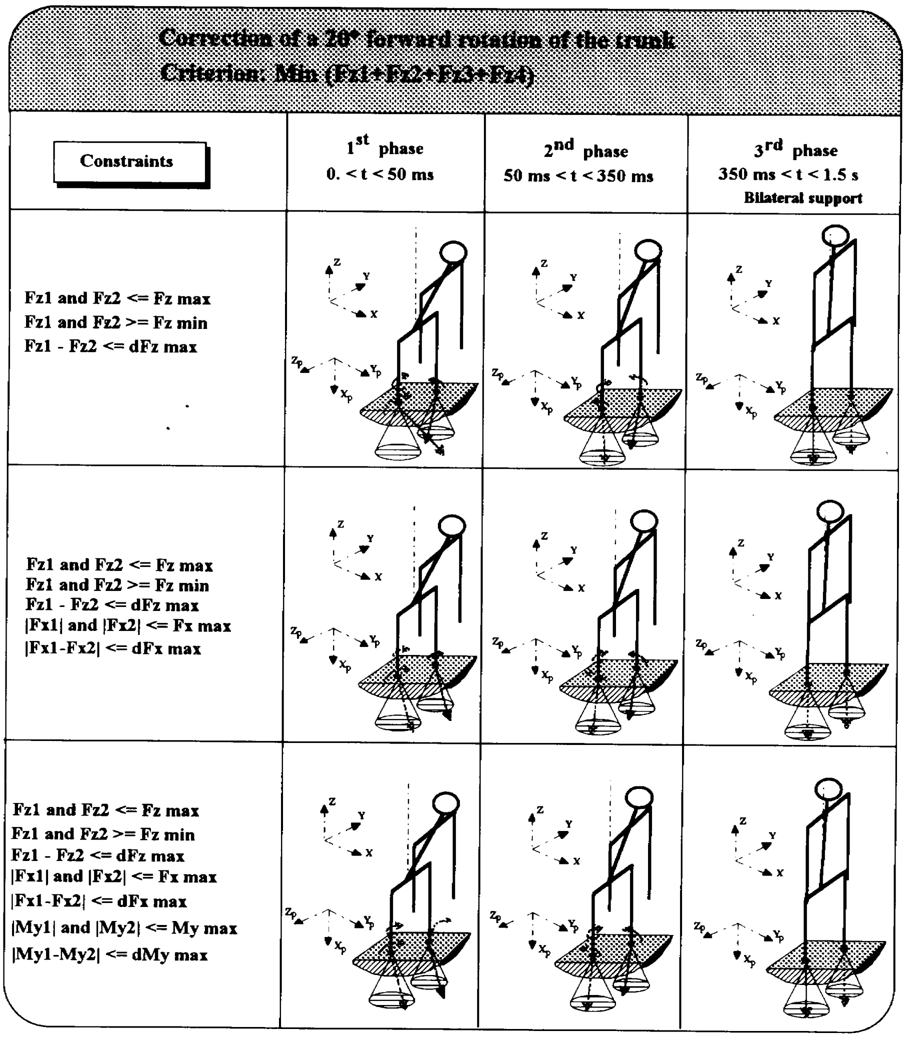

Fig. 5. Constraints influence.

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Fig. 6. Joint torques for right and left legs.

respect to the first criterion proposed (15). The forces/moments exerted by the feet on the ground, as well as friction cones, are represented. (X, Y, Z) is the absolute frame, while (X_p, Y_p, Z_p) is the frame at the tip of the legs.

According to the results corresponding to basic constraints (first line of the table), the movement has been broken into three phases: During the first phase which is very short, huge forces are developed to correct the trunk center of gravity position error. In a second phase, the angular error is corrected, then in a third phase the forces/moments are close to the static equilibrium forces distribution.

During the first phase, it clearly appears that the right leg slips because the force exerted by the right foot on the ground is outside the friction cone. Moreover, the exerted moments and then the joint torques are greater on the right side than on the left one (see Figure 6). Thus, additional constraints have been defined to circumvent these drawbacks which would lead to the biped fall. First, the antero-posterior forces (F_x) have been limited as well as the difference of these forces between the right and left sides (second line of the figure). The following constraints have been introduced:

$$(|F_{x_1}| \leq F_{X_{\max}}) \quad \text{or} \quad F_{x_1} \leq F_{x_{\max}}, \quad -F_{x_1} \leq F_{x_{\max}} \tag{20}$$

$$(|F_{x_2}|) \leq F_{x_{\max}}) \quad \text{or} \quad F_{x_2} \leq F_{x_{\max}}, \quad -F_{x_2} \leq F_{x_{\max}} \tag{21}$$

$$(|F_{x_1} - F_{x_2}| \leq \Delta F_{x_{\max}}) \quad \text{or} \quad F_{x_1} - F_{x_2} \leq \Delta F_{x_{\max}}, \quad -F_{x_1} + F_{x_2} \leq \Delta F_{x_{\max}} \tag{22}$$

This allows the force exerted by the right foot on the ground to stay inside the friction cone as shown by the second line of the figure. However, the difference between the moments on the right and left sides persists. In order to better share the moments exerted by the right and left feet on the ground, the moments exerted by the legs on the trunk along the lateral axis (M_y) have been limited by the following constraints (third line of the figure):

$$(|M_{y_1}| \leq M_{y_{\max}}) \quad \text{or} \quad M_{y_1} \leq M_{y_{\max}}, \quad -M_{y_1} \leq M_{y_{\max}} \tag{23}$$

$$(|M_{y_2}| \leq M_{y_{\max}}) \quad \text{or} \quad M_{y_2} \leq M_{y_{\max}}, \quad -M_{y_2} \leq M_{y_{\max}} \tag{24}$$

$$(|M_{y_1} - M_{y_2}| \leq \Delta M_{y_{\max}}) \quad \text{or} \quad M_{y_1} - M_{y_2} \leq M_{y_{\max}}, \quad -M_{y_1} + M_{y_2} \leq \Delta M_{y_{\max}} \tag{25}$$

During the second and the third phases, the interaction forces between the feet and the ground are less than during the first phase even when only the basic constraints are taken into account. Thus the additional constraints mainly allow a better distribution of the forces and moments between the right and left sides. This is illustrated by Figure 7 where the Zero Moment

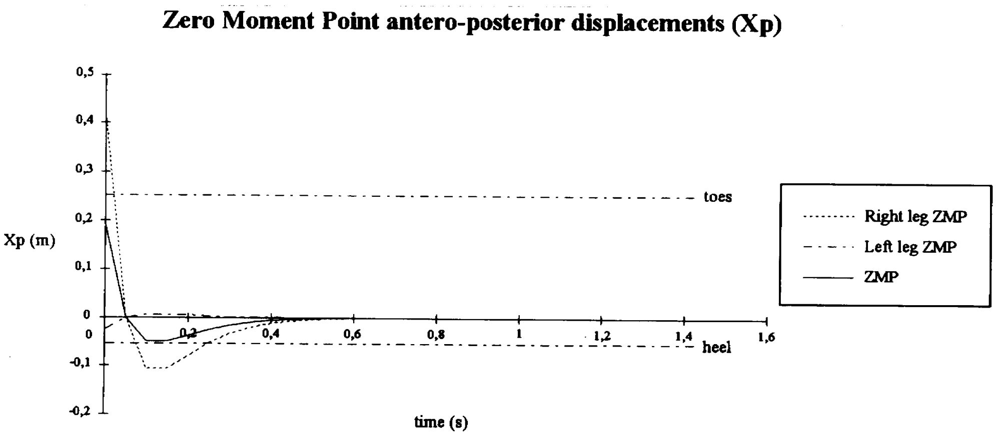

Fig. 7. Zero Moment Point antero-posterior displacements.

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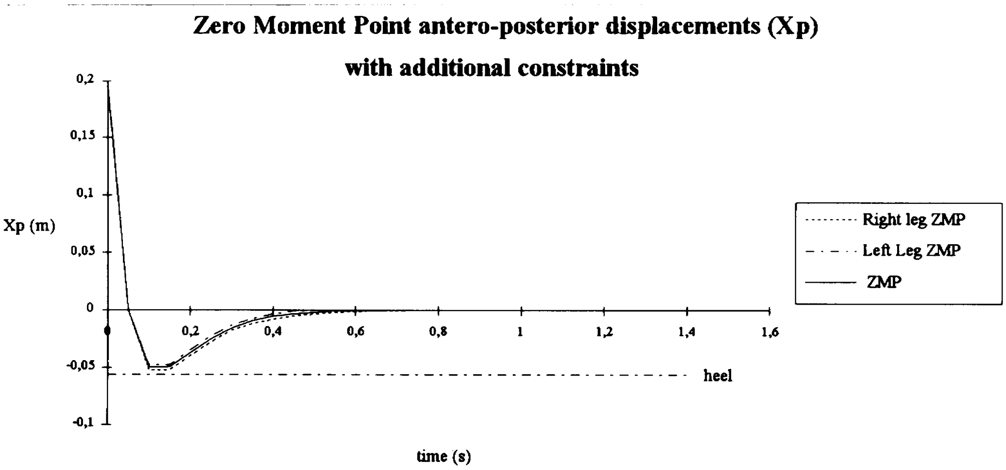

Fig. 7. Zero Moment Point antero-posterior displacements.

Point displacements with and without additional constraints are presented. So it appears that another way to decrease the interaction forces in the first phase would be to reduce K_p and K_v. However this would either prevent the asymptotic convergence on a solution or slow down this convergence in an unacceptable way.

3.4.3 **Perturbation influence.** The previous results have been obtained for a 20° forward rotation of the trunk. It has been pointed out that the most critical phase of the correction of this perturbation is the first one. Indeed, during this one, huge interaction forces are developed between the feet and the ground. In some cases this leads to sliding of one of the supporting legs which is not acceptable.

Figure 8 shows that, for the same simulation conditions, the sliding problems do not exist for small angular perturbations ($\Phi_y < 10°$). As soon as the

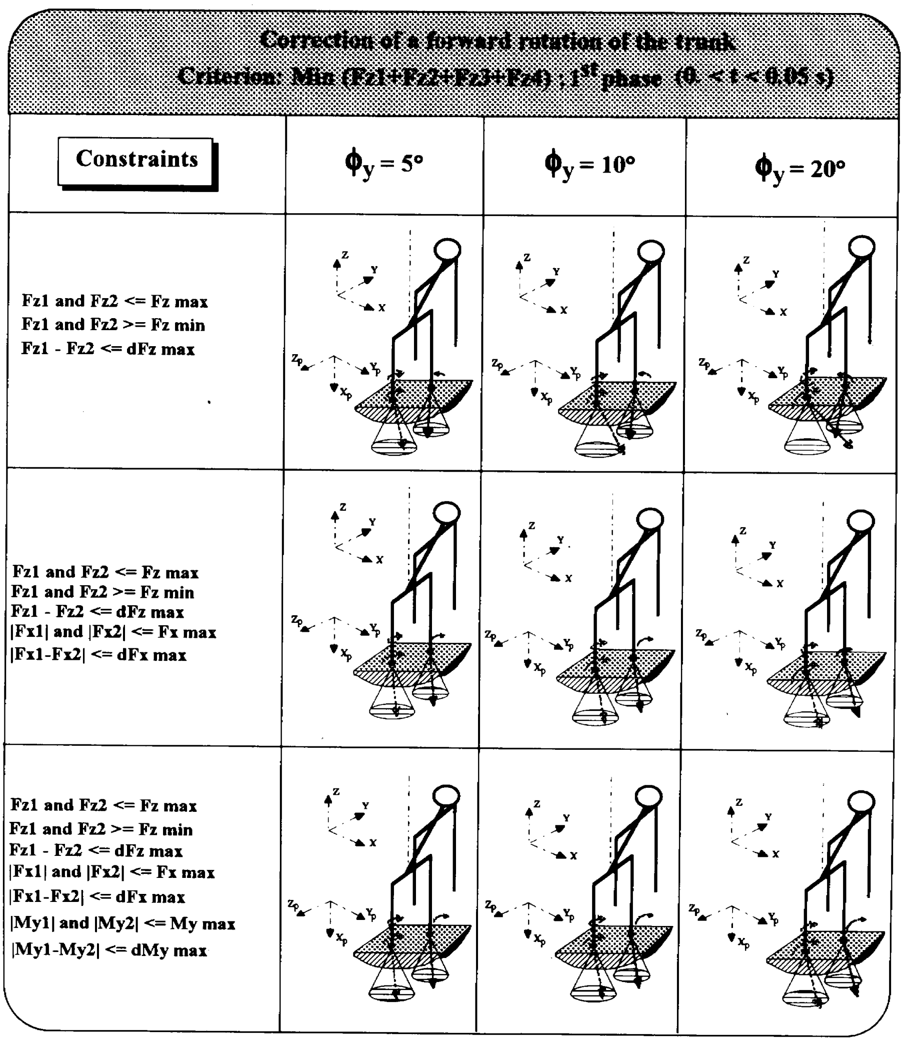

Fig. 8. Perturbation influence.

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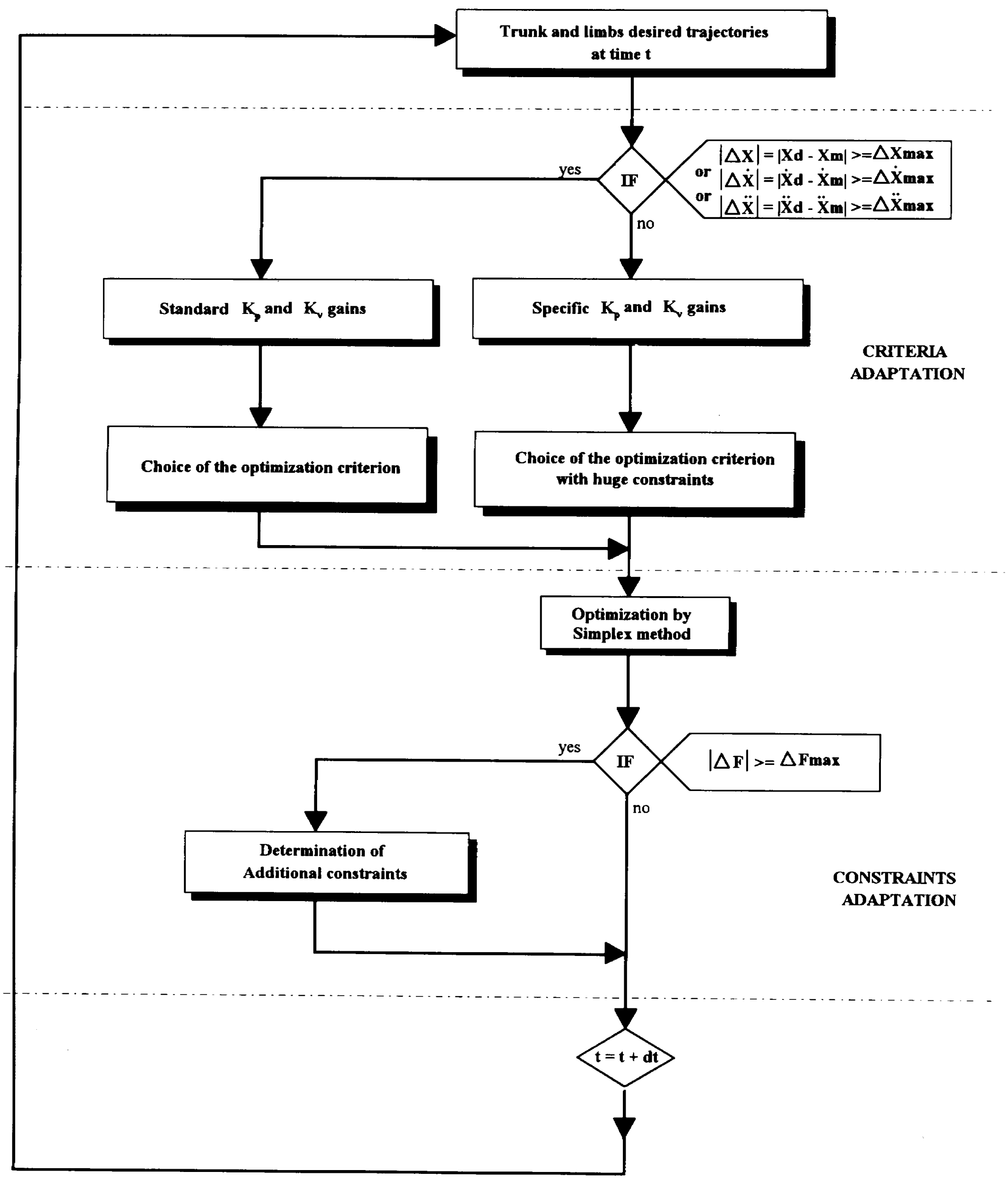

Fig. 9. *RTCA* approach.

perturbation is too strong, the force distribution problem becomes hardly solvable. This shows that the same criterion, constraints and gain values cannot be used in all perturbation cases to maintain the standing posture. All these variables must be adapted according to the perturbation. This is in agreement with the results of biomechanical studies of the human behaviour. Actually it has been demonstrated in biomechanical studies[23,24] that the human being adapts its postural control strategies with respect to the perturbation. Hence in the next section we present a modification of our method which allows real-time constraints, criteria and gain adaptation in order to insure our biped dynamic stability.

4. REAL TIME ADAPTATION APPROACH

In this section we propose to introduce a new concept which is called real time constraints and criteria adaptation for a biped dynamic stability. This has been called *RTCA* which is an acronym for "*R*eal *T*ime *C*riteria and constraints *A*daptation".

4.1 RTCA Principle

According to the previous results it seems that the values of the K_p and K_v gains and the criterion determine a total limbs/trunk interaction force/moment solution. The constraints enable to shareout these total forces and moments between the different limbs as long as the total solution can still be reached. That is to say that the constraints do not allow to modify the global solution but only allow to better share this solution between the limbs.

Thus, it appears that in case of perturbation the first requirement is to find a solution of the force distribution problem. This means that K_p, K_v and the optimization

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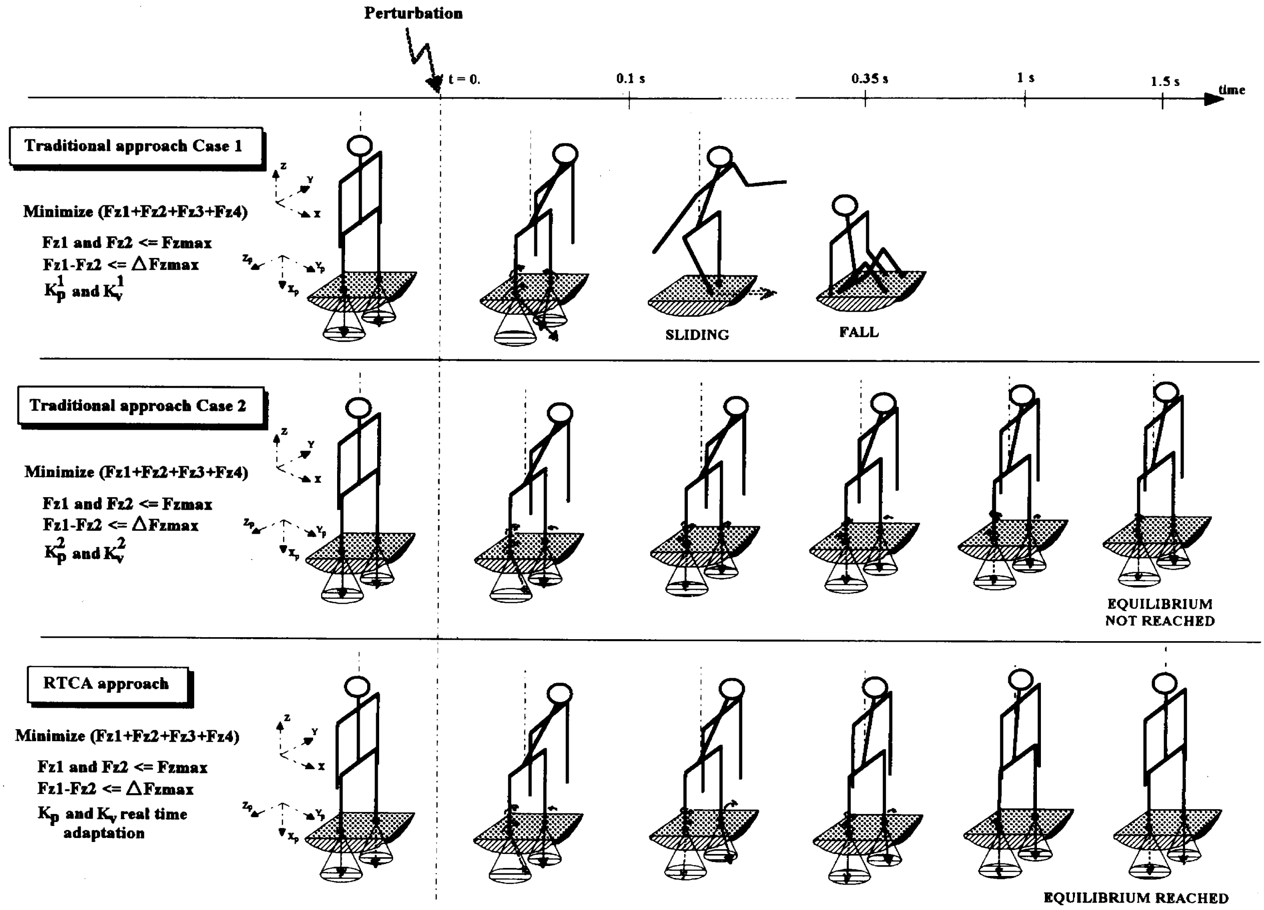

Fig. 10. Simulation results with and without *RTCA* approach.

criterion must be chosen with respect to the perturbation. A good sharing of the forces and moments is not immediately necessary. Anyway, the basic constraints must be satisfied in order to preserve the biped structure and its actuators.

In this way for our example, initial mean values of K_p and K_v gains seem recommended in order to prevent initial sliding, especially for a high forward angular perturbation ($\Phi_y > 10°$). However, these gains must next be increased in order to insure trunk trajectory convergence. In a general manner, it seems that the initial values of K_p and K_v gains must be small enough in order to prevent excessive forces to be generated. But they also must be high enough to insure asymptotic convergence. A good way to meet these two requirements is to real-time adapt the K_p and K_v gains values with respect to trunk trajectory errors. According to the section 3 results, the criterion also appeared to be task-dependent. Moreover, once a general solution has been found it can be better shared between the limbs at the following time step. Thus, we propose a real-time gains, criterion and constraint adaptation the principle of which is synthesized in Figure 9.

4.2 Simulation results

In order to prove the efficiency of this approach we present simulation results with and without, K_p and K_v gains values, criteria and constraints real-time adaptation.

The biped is initially in a standing posture. Its equilibrium is ensured with criterion (15). Then an external perturbation brings it in a 20° forward tilted position. The constraints are set to basic constraints. Figure 10 displays the biped behaviour for three simulation conditions: First, the K_p and K_v gains values are added to the values K_p^1 and K_v^1 which ensure fast convergence for small angular tilting ($\Phi_y < 10°$). Sliding occurs which involves a biped fall. Then, the K_p and K_v gains values are added to the values K_p^2 and K_v^2 which prevents initial sliding. Unfortunately, these gains are too low to bring the biped back to its equilibrium position within 1.5 s. Such a long convergence time is not acceptable. Finally, real-time adaptation realizes a compromise by choosing low gains values (K_p^2, K_v^2) during the first time steps in order to prevent sliding and then high gains values (K_p^1, K_v^1) to ensure an asymptotic trunk trajectory convergence.

These results clearly demonstrate that the *RTCA* approach allows one to find a convenient correction to an external perturbation in a case where a traditional fixed criteria approach does not find a solution.

5. CONCLUSION

In this paper, we have proposed a new approach called *RTCA* (*R*eal *T*ime *C*riteria and constraints *A*daptation) which allows to real time adapt the criteria used for the

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dynamic stability of a biped called "*BIPMAN*". For that we rely on a multi-chain mechanical model and a control architecture which are more detailed in reference 9. First, we have shown how criteria and constraints can modify the forces distribution which ensures biped dynamic stability with respect to an external perturbation. According to these results we present the general principle of an *RTCA* approach which is then validated through new simulation results.

Future work will use this approach to solve the tasks transition problem, first through simulations and then applied to our biped.

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