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Dragomir N. Nenchev
Tokyo City University

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Experimental Validation of Ankle and Hip Strategies for Balance Recovery with a Biped Subjected to an Impact

Dragomir N. Nenchev and Akinori Nishio

Abstract— **A humanoid robot should be able to keep balance even in the presence of disturbing forces. Studies of human body reaction patterns to sudden external forces (impacts) are useful in developing balance control strategies. In this paper we show how to implement two such reaction patterns, called ankle and hip strategy, using a small humanoid robot. Simple dynamical models in the sagittal plane are employed. The decision for invoking one of the reaction patterns is based on acceleration data measured during the impact. The experiments confirm that the robot is able to react swiftly, resembling the reaction patterns of humans.**

I. Introduction

Humanoid robots are expected to operate within environments shared with humans. Consequently, special attention should be paid to safety of operation — a major problem still to be addressed thoroughly. Under safety of operation we understand not only the problem of how to prevent damage of the robot itself, when it falls down for example [1], but first of all, how to prevent the robot from falling down whatsoever.

Closely related to safety of operation is the problem of balance control. This problem has been studied mostly in relation to walking pattern generation, by taking into account the Zero Moment Point (ZMP) location (see e.g. [2], [3]). In [4] it was shown that when walking on uneven terrain, balance control can be improved by grasping suitable static objects from the environment. Balance control while lifting an object has been addressed in [5]. Balance control plays also an important role with regard to unexpected changes in the environment, such as keeping upright posture on a changing slope [6], walk on uneven terrain [7], or "emergency stop" type reaction when an obstacle appears suddenly on the path of the robot [8]–[10].

Another representative example of a balance control problem is quick balance recovery after the robot has been subjected to an unexpected external impact force while standing upright. Such a force could be caused by accidental collisions with humans or other surrounding objects. P. Gorce has addressed the problem via a hierarchical control structure [11] that includes a "coordinator" level with optimization capability based on the Simplex method. It should be noted that human body reaction for recovering balance under similar circumstances has been investigated extensively in the biomechanics and physical therapy literature. This lead to the recognition of two distinctive patterns of response to the impact, called "ankle" and "hip" strategy [12]–[15]. Based on these strategies, a continuum of different postural movements can be synthesized [13].

So far, the two strategies have been adapted to bipeds, though only in simulation studies [16]–[18]. The main emphasis has been put on the hip strategy thereby. Azevedo, Poignet and Espiau [17] derived a postural control method for a seven-joint planar biped using quadratic programming. Abdallah and Goswami [18] proposed a two-phase strategy for balance recovery and applied it to a planar four-link biped. In these works, no attention has been paid to a natural looking balance recovery pattern, as observed in humans, though.

In a recent paper [19], we addressed the adaptation of the hip strategy with a real biped HOAP-2 of Fujitsu Automation [20], based on the Reaction Null Space Method, developed originally for base disturbance control of free-flying [21] or flexible-base mounted space robots [22]. The simulations and off-line experiments with the robot confirmed that the method is efficient and that the resultant pattern is similar to that of a human.

The aim of the present work is twofold. First, we extend our previous study with the ankle strategy. Second, we aim at experimental validation in real-time, using a sensor-based approach that allows to initialize the most appropriate balance recovery strategy based on impact force data, obtained from the embedded acceleration sensor of the robot.

The paper is organized in four sections. Section 2 introduces the dynamical models for the ankle and hip strategies. Section 3 discusses implementation details and provides analysis of experimental data. The conclusions are given in Section 4.

II. Dynamical Models for the Hip and Ankle Strategies

It has been confirmed in the biomechanics and rehabilitation literature that the ankle and hip strategies ensure static balance, such that the center of mass (CoM) stays always within the base of support (BoS). The ankle strategy, for example, displaces the CoM slightly when the standing upright posture is perturbed. It was found out that this strategy is realized through ankle torque only. The hip strategy, on the other hand, minimizes the displacement of the CoM from the vertical by applying a torque in the hips mainly [14]. Hence, it is apparent that each strategy should be addressed via its own dynamical model.

Fig. 1 shows the models for the ankle and hip strategies proposed here. Both models include a spring-damper to

The authors are with Musashi Institute of Technology, Tokyo 158-8557, Japan.

All correspondence should be addressed to D. N. Nenchev (Yoshikazu Kanamiya) nenchev@sc.musashi-tech.ac.jp.

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ensure compliance with the impact force, either by ankle motion (Fig. 1 (a)), or by hip/ankle motion (Fig. 1 (b)).

The impact force is evaluated via the acceleration sensor, embedded in the chest of HOAP-2. The data is used then to decide which one of the two strategies is to be invoked.

A. Ankle strategy dynamical model

The ankle strategy is modeled after an inverted pendulum. The equation of motion is:

$$I\ddot{\theta} - mgl_g \sin\theta = -C\dot{\theta} - K\theta, \tag{1}$$

where $I \equiv I' + ml_g^2$, I' is the moment of inertia, and the other parameters are obvious form the model (see Fig. 1 (a)). This equation is simplified by ignoring the gravity term, which is justified by the high gear ratios and the internal high-gain feedback controller of HOAP-2. We obtain then the reference ankle joint acceleration as:

$$\ddot{\theta}^{ref} = -(C\dot{\theta} + K\theta)/I. \tag{2}$$

Next, we consider the moment balance equation during impact:

$$I\ddot{\theta} = mal_g, \tag{3}$$

where a is the measured acceleration. Assuming a small impact time interval Δt, and using the relation $\ddot{\theta} = \Delta\dot{\theta}/\Delta t$, we obtain the ankle joint angular speed step change as

$$\Delta\dot{\theta} = mal_g\Delta t/I. \tag{4}$$

The step change determines the initial state for the post-impact motion. The latter is calculated from the joint acceleration in (2). The acceleration is then integrated twice to obtain the reference ankle joint angle $\theta^{ref}(t)$, which is finally fed to HOAP-2's internal controller for execution. With this method, the robot reacts faster to larger impact forces.

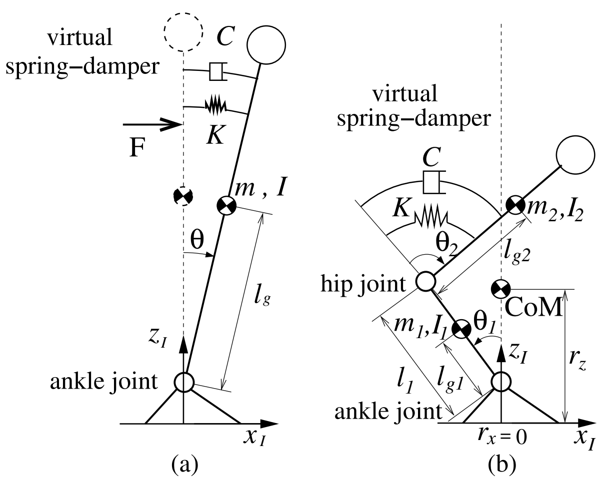

Fig. 1. Ankle (a) and hip (b) strategy dynamical models.

B. Hip strategy dynamical model

The model is derived with the help of the Reaction Null-Space method, originally developed to deal with the problem of base disturbance of free-flying or flexible-base mounted space robots [21]. In [19], we have shown how the method can be adopted for the hip strategy. In order to minimize the displacement of the CoM from the vertical, one needs to compute the null-space of the so-called "inertia coupling matrix" — a submatrix of the total inertia tensor that provides the inertial coupling forces between the foot and the rest of the links.

Assume a biped in balance with motionless support foot and vertical reaction passing through the CoM (see Fig. 1 (b)). Such a state can be easily maintained, provided the imposed wrenches at the support foot, due to link motions, are summed up to zero. According to the Reaction Null-Space method, all joint accelerations/velocities that would maintain the balance are given as:

$$\ddot{\boldsymbol{\theta}} = -\boldsymbol{H}_{fl}^{+}\dot{\boldsymbol{H}}_{fl}\dot{\boldsymbol{\theta}} + (\boldsymbol{I} - \boldsymbol{H}_{fl}^{+}\boldsymbol{H}_{fl})\boldsymbol{\xi}_2 \tag{5}$$

and

$$\dot{\boldsymbol{\theta}} = (\boldsymbol{I} - \boldsymbol{H}_{fl}^{+}\boldsymbol{H}_{fl})\boldsymbol{\xi}_1 \tag{6}$$

respectively. Here, $\boldsymbol{\theta} \in \Re^n$ denotes the vector of joint variables, $\boldsymbol{H}_{fl} \in \Re^{m\times n}$ is the inertia coupling matrix, and $\boldsymbol{\xi}_2, \boldsymbol{\xi}_1 \in \Re^n$ are arbitrary vectors. m denotes the degree of freedom (DOF) of the foot, while n stands for the number of joints.

A necessary condition for the existence of the Reaction Null-Space is that the number of joints n should be larger than the DOF of the foot. Note that this is *not* the case with our planar model, which has just two joints, the ankle and the hip joints ($n = 2$), and a foot with three DOF (two for translation and one for rotation $m = 3$). The inertia coupling matrix $\boldsymbol{H}_{fl}$ is 3×2, then, and we have an underactuated system at hand. We can make use of the *selective* Reaction Null-Space [21], though, to control particular components of the imposed wrench. For the planar model, the particular component to be controlled is the imposed force component at the foot in the horizontal x direction — it should be zero. This means that the total CoM will stay on the vertical, and no moment will be generated at the foot from the CoM motion. In other words, we ignore the imposed force component in the z direction and the moment at the foot.

In this case, the inertia coupling matrix $\boldsymbol{H}_{fl}$ is 1×2:

$$\boldsymbol{H}_{fl} = \begin{bmatrix} r_z(m_1 + m_2) & m_2 l_{g2} C_{12} \end{bmatrix}, \tag{7}$$

where

$$r_z = \frac{(m_1 l_{g1} + m_2 l_1)C_1 + m_2 l_{g2} C_{12})}{m_1 + m_2} \tag{8}$$

is the z component of the CoM position vector, and $C_1 = \cos\theta_1$, $C_{12} = \cos(\theta_1 + \theta_2)$. The selective Reaction Null-Space is one-dimensional, containing the set of joint velocities:

$$\dot{\boldsymbol{\theta}} = b\boldsymbol{n}, \tag{9}$$

where b is an arbitrary scalar, and the null-space vector is

$$\boldsymbol{n} = \begin{bmatrix} -m_2 l_{g2} C_{12} \\ (m_1 l_{g1} + m_2 l_1) C_1 + m_2 l g_2 C_{12} \end{bmatrix}. \tag{10}$$

Finally, eliminate b from the last two equations to obtain the following relation between the two joint speeds:

$$\dot{\theta}_1 = \frac{-m_2 l_{g2} C_{12}}{(m_1 l_{g1} + m_2 l_1) C_1 + m_2 l_{g2} C_{12}} \dot{\theta}_2. \tag{11}$$

This relation satisfies the following constraint equation:

$$\dot{r}_x = \begin{bmatrix} r_z & \frac{m_2 l_{g2} C_{12}}{m_1 + m_2} \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 & \dot{\theta}_2 \end{bmatrix}^T = 0. \tag{12}$$

III. EXPERIMENTS

A set of experiments for the two strategies have been performed with a HOAP-2 humanoid robot. The impact force is evaluated via the acceleration sensor, embedded in the chest of HOAP-2. The data is used then to decide which one of the two strategies is to be invoked. For this purpose, we determined experimentally a threshold for the impact acceleration. Impacts, with acceleration values below/above the threshold, invoke the ankle/hip strategy, respectively.

The dynamical models for the two strategies are used to generate reference input data for the controller. The latter is just a conventional PD controller.

A. Ankle strategy experiment

The dynamic parameters for the inverted pendulum model are calculated based on HOAP-2's data, as $I' = 0.101$ kgm^2, $l_g = 0.239$ m and $m = 6.75$ kg. The robot was subjected to an impact force by hand on the back. The impact time interval was selected as $\Delta t = 1$ ms, which is the sampling time interval of the system.

In order to obtain a satisfactory behavior, the virtual spring-damper related parameters had to be selected in an empirical way. We used time-variable spring-damper coefficients $C(t)$ and $K(t)$, derived from 5th order polynomials. The initial and final values of the coefficients were determined experimentally as $K^{init} = 5.0$ Nm/rad,$K^{final} = 8.0$ Nm/rad, and $C^{init} = 3.0$ Nms/rad, $C^{final} = 5.0$ Nms/rad, respectively. The final time t_f for the polynomials was selected as $t_f = 1.0$ s. The initial spring constant has a lower value than the final one, because we had to ensure quick response to the impact (an admittance-type behavior immediately after the impact), and quick posture recovery via the higher final spring constant, in the second phase.

The experimental data graphs and snapshots of HOAP-2's motion for an acceleration of $a = 0.89$ m/s^2, are shown in Fig. 2. It is seen that the displacement of the CoM is predominantly in the x direction. The step change in angular speed is about -0.75 rad/s. The ZMP graph shows that the ZMP remains within the BoS (between the "heel" and "toe" lines in the graph), and that the balance recovery pattern is stable. The data in the ZMP graph, as well as these in the vertical reaction force graph, are calculated from the pressure sensors of the left and the right foot. Note that the robot is not perfectly symmetrical, therefore one should not expect perfect match for left and right, even in the case of a planar model.

We made another experiment to demonstrate how the reaction pattern changes with a larger impact force. Figure 3 shows the data graphs for an acceleration of $a = 1.00$ m/s^2. Though the step change in angular speed seems to be just a bit larger than in the previous experiment, from the ZMP graph it is apparent that the ZMP stays for relatively long time, first at the "toe" boundary, than at the "heel" boundary. This indicates posture instability and we can conlude that the robot was not able to maintain balance. We can conclude also, that the impact acceleration threshold for invoking the hip strategy should be less than the critical impact acceleration used in this experiment.

B. Hip strategy experiment

The kinematic and dynamic parameters for the hip strategy model (cf. Fig. 1 (b)) are shown in Table I.

Here also, time-variable spring-damper coefficients had to be used. The initial and final values for the 5th order polynomials for the coefficients were determined experimentally as $K^{init} = 0.1$ Nm/rad, $K^{final} = 0.7$ Nm/rad, and $C^{init} = 0.06$ Nms/rad, $C^{final} = 0.4$ Nms/rad, respectively. The final time t_f for the polynomials was selected as $t_f = 1.5$ s.

We performed three experiments. In the first experiment, a relatively strong impact force was applied from the back, imposing an acceleration of $a = 2.48$ m/s^2. The respective graphs are shown in Fig. 4. It is apparent that the CoM is displaced mainly in the vertical z direction. The motion in the hip joint is quite quick, as seen from the joint velocity graph. The ZMP graph shows that despite the swift reaction, the robot is able to maintain balance. The ZMP is displaced significantly and almost reaches the toe tip. Hence, the impact force in this experiment can be considered as the limit for the hip strategy.

In the next experiment, a relatively week impact force was applied from the back, yielding an impact acceleration of $a = 0.97$ m/s^2. This is slightly below the impact acceleration of $a = 1.00$ m/s^2 for which the robot couldn't maintain balance during the second ankle strategy experiment (the case without success). As can be seen from the experimental data graphs and the respective snapshots in Fig. 5, the robot is able to keep balance now, under the hip strategy. The CoM is thereby only slightly displaced from the vertical. The variation of the ZMP is also quite small. From this experiment, we can conclude that the acceleration threshold for invoking the hip strategy should be set to less than 0.97 m/s^2.

In the final experiment under the hip strategy, the impact

TABLE I

LINK PARAMETERS FOR THE HIP STRATEGY MODEL

Parameter	m	I	l	l_g
Unit	[kg]	[kgm^2]	[mm]	[mm]
Link 1	1.450	0.0057789	200	82.05
Link 2	4.961	0.03214829		10.251

force was applied to the chest of the robot. The acceleration was $a = -1.07$ m/s^2, which implies a relatively week force. The respective graphs and snapshots are shown in Fig. 6. It is seen that the robot reacts in bending in the appropriate direction, with insignificant displacement of the ZMP. We can conclude then that the balance in this case can be maintained as well.

IV. CONCLUSIONS

The paper illustrated how the ankle and hip strategies — two well-known reaction patterns for balance recovery of a human subjected to a sudden external force while standing upright — can be modeled and applied to a humanoid robot. Each of the two strategies was modeled by a simple planar dynamical model in the sagittal plane. In the case of the hip strategy, especially, we could avoid optimization algorithms by adapting the Reaction Null-Space method — a method developed originally for free-flying and flexible-base space robots. The method can be applied to control balance in response to other external perturbations as well, and is easily extendable to the general, three-dimensional case.

We have shown that the acceleration data, measured during posture perturbation, can be used in two ways: (1) to modify the speed of reaction for the specific reaction pattern, and (2), to invoke one of the two strategies, depending on the experimentally determined threshold. Our models include virtual spring-dampers used to generate reference trajectories for the reaction patterns. Since our goal was to mimic human behavior, and no appropriate data was available, we had to set the respective parameters on an empirical basis. Further analysis is needed, though, to devise a method for this purpose. Also, in a future work, we plan to make use of impact impulse data, in addition to the impact acceleration, and to enlarge the set of reaction patterns.

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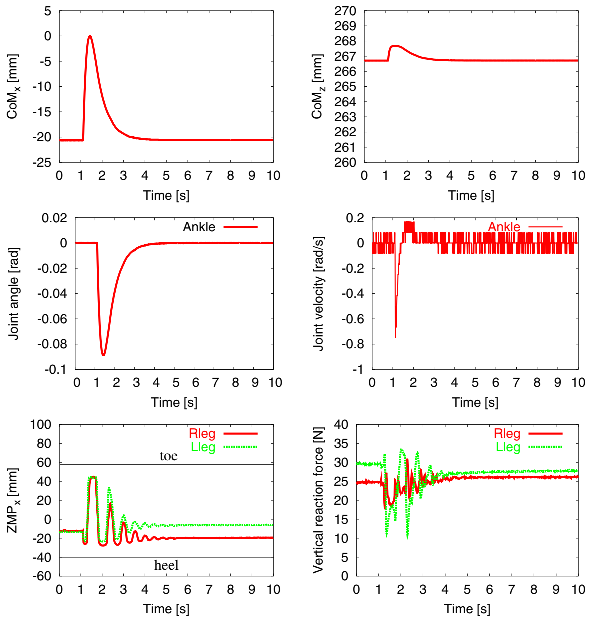

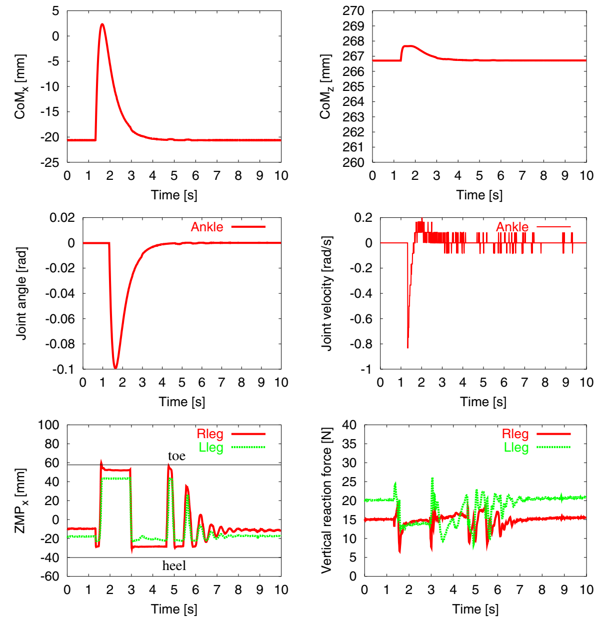

Fig. 3. Ankle strategy without success.

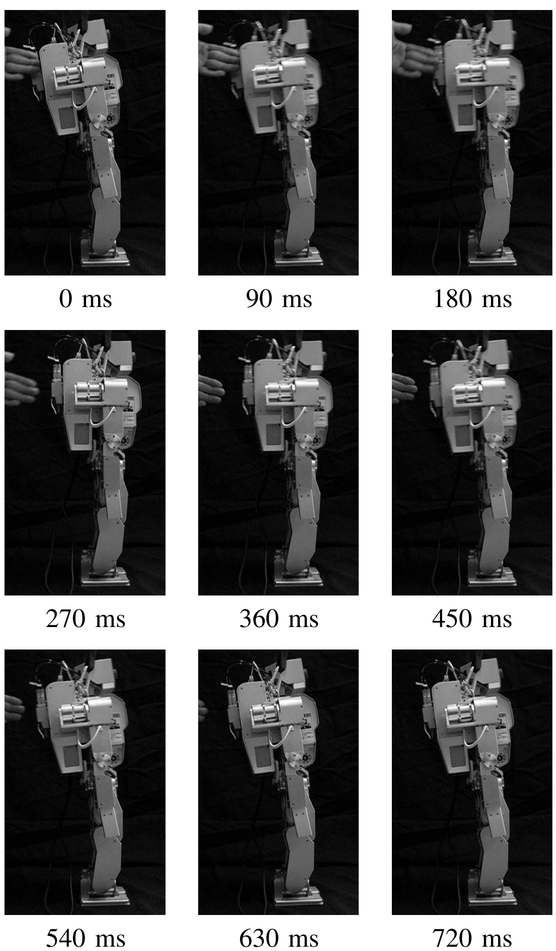

Fig. 2. Ankle strategy with success.

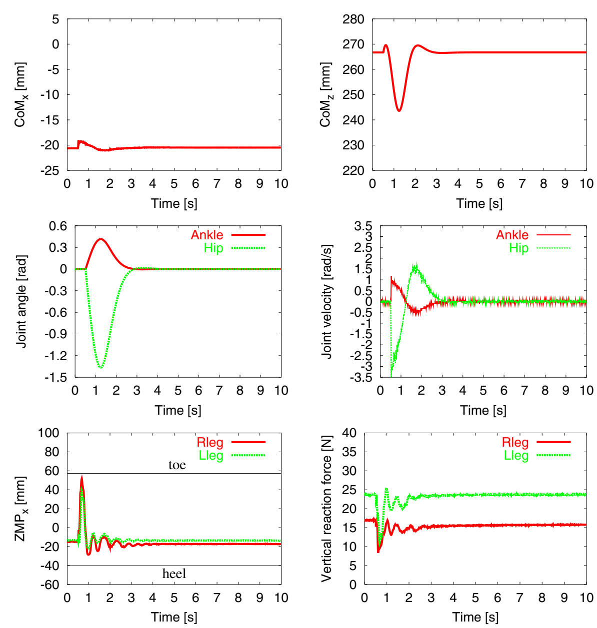

Fig. 4. Hip strategy under a relatively strong force on the back.

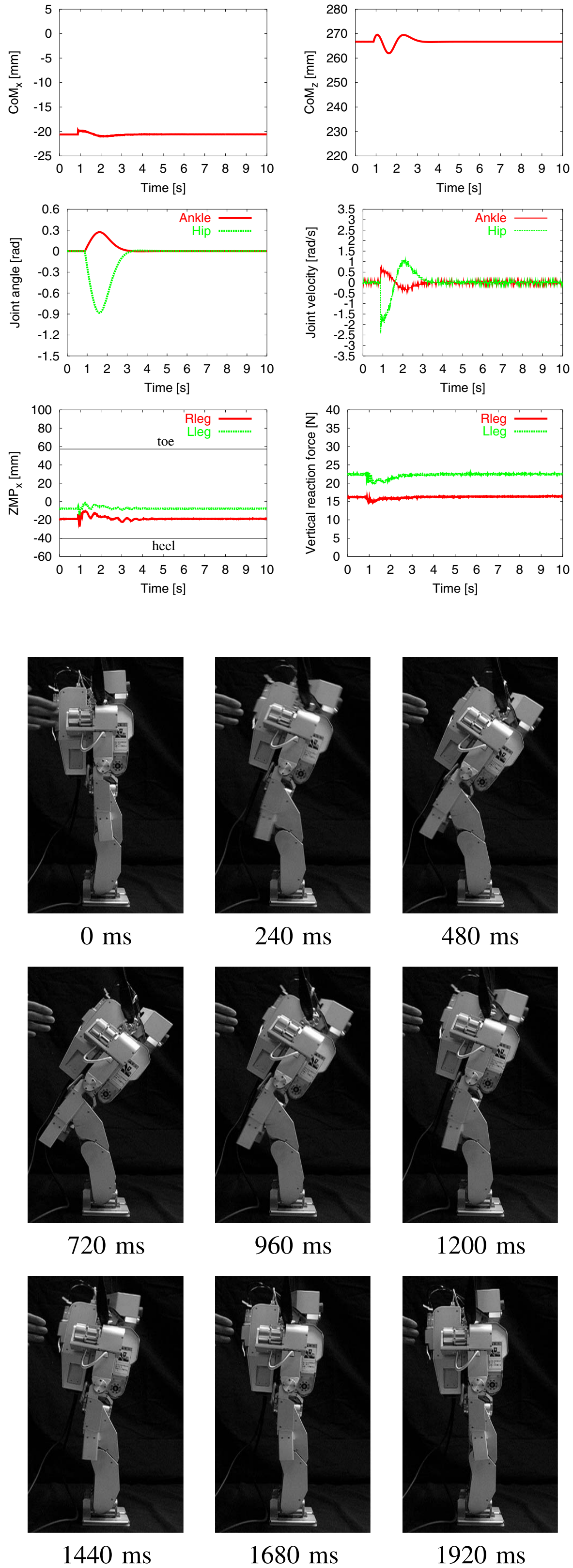

Fig. 5. Hip strategy under a relatively week impact on the back.

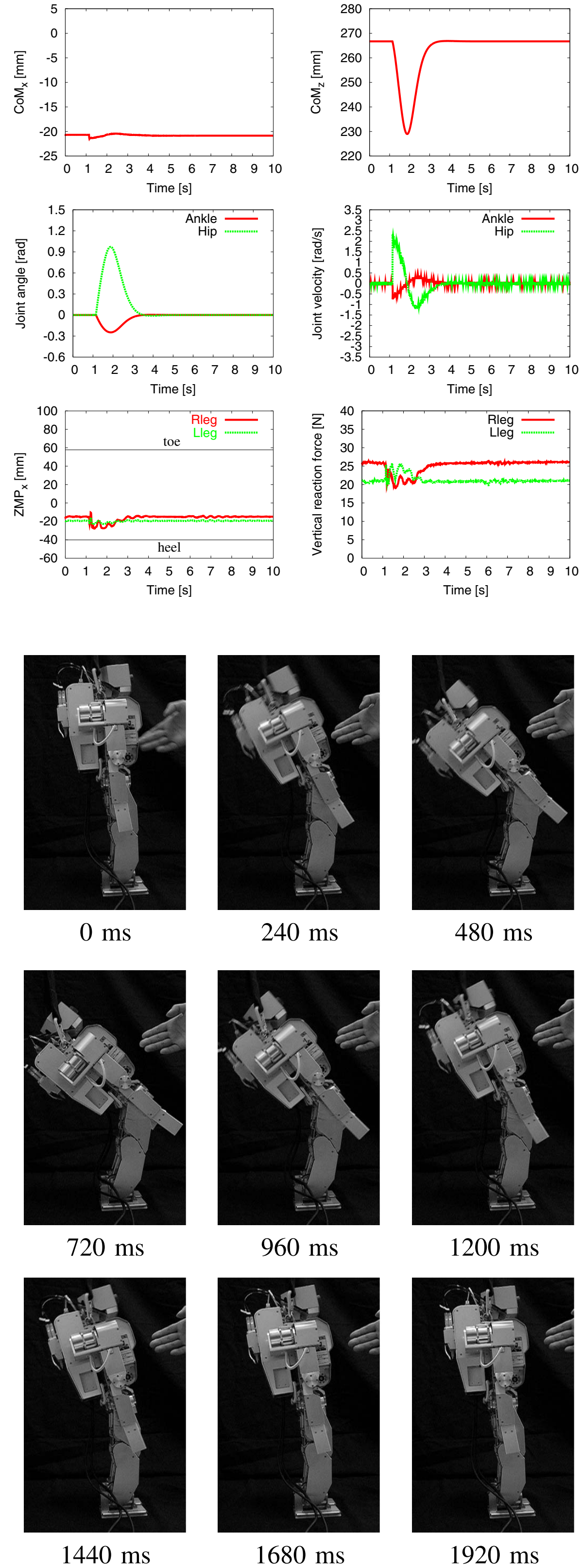

Fig. 6. Hip strategy under an impact on the chest.