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The First Human-size Humanoid that can Fall Over Safely and Stand-up Again

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Abstract— **This paper investigates a method through which a human-size humanoid robot can fall over backwards safely. Squatting-extending motion of legs reduce impact of falling and shock-absorbing parts of the robot keep the force at a permissible range. The robot could stand up itself again after falling.**

I. INTRODUCTION

Biped humanoid robots have several advantages over the conventional mobile robots since it can step over obstacles and go up and down stairs. However, as a major disadvantage they may fall over, which in turn can lead to failure due to excessive damage. This is one of the crucial barriers for practical application of humanoid robots. Humanoid robots cannot be accepted for use in society unless this problem is overcome.

Compared with quadruped walking robots or wheeled ones, the center of gravity of a biped-walking robot is located at a relatively high position and the size of the convex hull of the feet is smaller. A biped humanoid robot is essentially an unstable structure, and as such, little can be done to prevent the robot from falling over. In addition, the robot may be damaged seriously enough to prevent it from walking thereafter, since the impact between the robot and the ground may be large. The bigger the humanoid robot the more serious the damage can be. It is therefore important to address this problem.

Recently humanoid robotics is at an exciting stage[1], [2], [3] after the astonishing debut of the Honda P2[4]. Biped locomotion is being intensively studied, and the controller of Honda's robots is considered state of the art in this field. However, little has been reported on how to enable a humanoid robot to fall over safely and prevent it from being damaged.

The goal of our research is to prevent physical damage that would disable the locomotive ability of the robot, thus giving it a chance to stand up again.

We proposed "UKEMI" strategy, a falling motion control to minimize damage to humanoid robots[5]. In this paper, we make further analysis of damage reduction and perform experiments using real human-sized robots. We believe this is the first report of a human-size humanoid robot that cans fall over safely and also stand-up itself again.

This paper is organized as follows. In Section 2, we analyze the falling motion of a simple inverted pendulum and propose a feasible control that might reduce damage on impact. The robots for fall over experiments HRP-2LF and HRP-2P are explained in Section 3. Preliminary experiments using these hardware are also presented. Section 4 describes our fall over experiment with HRP-2P humanoid robot in detail. We conclude the paper in Section 5.

II. FALLING MOTION CONTROL

A. Basic strategy of the falling motion control

In this section, we analyze falling motion using a simple model to establish a basic control strategy. Since the falling robot cannot apply an external moment onto the ground, it can be modeled as a simple inverted pendulum with a passive joint. In addition, we assume the pendulum can change its leg length to emulate the knee bending effect of a squatting motion(Figure 1, right).

The dynamics of the pendulum is given by

$$r^2\ddot{\theta} + 2r\dot{r}\dot{\theta} + gr\cos\theta = 0, \tag{1}$$

$$\ddot{r} - r\dot{\theta}^2 + g\sin\theta = f/m, \tag{2}$$

where r is the distance between the fulcrum and the center of gravity, θ is the angle of the pendulum measured from horizontal line, m is the total mass, f is the force of the leg extension and g is gravity acceleration.

Let us call the vertical speed of the mass at hitting the ground, the *landing speed*. Apparently, the landing speed is closely related to the damage at the impact. So now, our goal is to minimize the landing speed by means of the only input f, the leg extension force.

For this purpose, we decided to use simple heuristics instead of taking rigorous optimization technique. At the beginning of the fall, f is controlled so that the leg shrinks to the specified minimum length r_{min} from the initial length r_0 as fast as possible. To keep the foot (fulcrum) on the ground, f is bounded not to generate the vertical acceleration larger than g. Immediately after the pendulum reaches the specified switching angle θ_1, f is applied to extend the leg. By this leg extension, we can make the moment of inertia larger and it reduces the angular velocity $\dot{\theta}$. As a result, we can obtain smaller landing speed by this leg extension.

The graph on the left of Fig. 1 shows the landing speed with a set of the minimum length r_{min} and the switching angles θ_1. This is a simulation result using equations (1) and (2) with parameters of $m = 1$ [kg] and $r_0 = 1$ [m]. In the graph, we can observe that a certain set of r_{min} and θ_1 can make landing speed almost half compared with other settings.

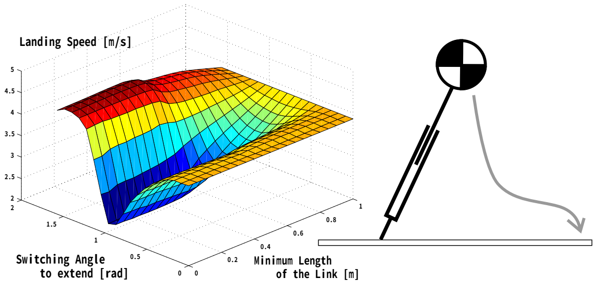


Fig. 1. control landing motions

B. The Algorithm

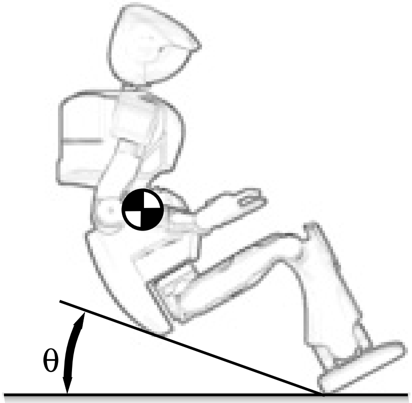


Fig. 2. falling angle θ

Based on the simulation result of the inverted pendulum, we constructed a control algorithm for a humanoid robot to fall down safely. This algorithm goes through a series of five states. First before going into the algorithm is the STANDBY stage in which the robot is standing upright. This is the state in which the stabilizer is in control of the robot and keeps it standing straight[6]. In the case of a high impact such as the robot getting knocked down by a human, the COG point can be pushed past the limits at which the stabilizer can keep the robot upright.

SQUATTING State: When the center of gravity(COG) of the robot deviates from the support polygon of the feet, the fall over controlling module suppresses the stabilizer and other motion generating modules that may be operating and the robot goes into the SQUATTING stage. In this state, the Fall over controlling module calculates which part of the body would land first, the knees are bent so that and the robot squats down to restrain the force of impact. The neck, waist and arms are curled up into the landing posture.

EXTEND1 State: When angle θ which is defined by the angle between the horizontal plane and the extended line including the heel and hip of the robot (Fig. 2), reaches angle θ_1 the legs of the robot are extended to decrease angular velocity as explained in the previous section. This also enables the robot to land in a position that would enable the maximum amount of cushioning to be used on impact.

TOUCHDOWN State: When the robot actually falls to the ground the servomotors are switched off to minimize damage to the mechanical parts such as gears after $\theta < \theta_2$.

EXTEND2 State: T_1[sec] after touchdown the robot switches on the servomotors to prevent it from rolling too far backwards. If it does, it can damage the head, which house the cameras and is delicate. The actual amount of time to wait after touchdown was found from actual experimentation.

FINISH State: T_2[sec] after touchdown the robot lies straight on the ground to prepare to get up again. The amount of time to wait was also derived through experimentation. The algorithm is summarized in Table I

TABLE I

Stage	Trigger	
STANDBY		
SQUATTING	$COG_x < heel_x$	
EXTEND 1	$\theta < \theta_1$	
TOUCHDOWN	$\theta < \theta_2$	$t = 0$
EXTEND 2	$t > T_1$	
FINISH	$t > T_2$	

III. PRELIMINARY EXPERIMENTS

A. HRP-2P and HRP-2LF

Our target humanoid robot, HRP-2P(Fig. 3 left) is full-bodied with 30 D.O.F., complete with cameras in the head

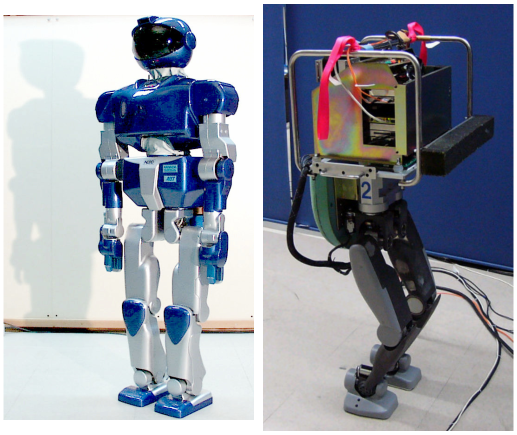


Fig. 3. HRP-2P (left) and HRP-2LF (right)

TABLE II

Specifications of HRP-2P

HRP-2P (Humanoid robot)	
Legs	6 D.O.F./Leg (Hip:3 Knee:1 Ankle:2) Upper leg length: 0.3[m] Lower leg length: 0.3[m] Ankle height: 0.1 [m]
Waist	2 D.O.F (Yaw:1 Pitch:1)
Arms	6 D.O.F./Arm (Shoulder:3 Elbow:1 Wrist:2)
Hands	1 D.O.F./Hand
Neck	2 D.O.F. (Yaw:1 Pitch:1)
Height (standing straight)	1.58 [m] (floor–top) 0.81 [m] (floor–center of mass)
Weight	Total 58 [kg]

for stereo vision[7]. Experimenting with this robot using an algorithm that still required parameter tuning would only create excess time and labor with a risk of damage at each time. We therefore started our experiment with a simpler robot, the HRP-2LF(Fig. 3 right). The HRP-2LF was originally built as the HRP-2L, which is a leg module used as a test bed to study various techniques for walking[8]. The dimension of its legs and its total weight are similar to the HRP-2P. The modifications we made to HRP-2L are listed below.

- A frame with a cushion corresponding to HRP-2P's hip was added.
- Whole computer block was protected with a roll bar.
- The computer block was floated from the main frame with anti-vibration mounts.
- Tensioner elements were provided to each board in computer to make connections robust to vibration.
- External battery was used instead of interior because of shortage of the space needed by anti-vibration mounts.
- Reflective memory was added to preserve the log data even when the on-board computer is killed by the impact.
- Accelerometers were added to the X-axis and Z-axis of the main frame and the X-axis of the computer block(Fig. 4-right).

TABLE III

Specifications of HRP-2LF

HRP-2LF (Biped robot)	
Legs	6 D.O.F./Leg (Hip:3 Knee:1 Ankle:2) Upper leg length: 0.3[m] Lower leg length: 0.3[m] Ankle height: 0.09 [m]
Height	1.41 [m] (floor–top) 0.77 [m] (floor–center of mass)
Weight	Dummy weights 22.6[kg] Total 44.3 [kg]

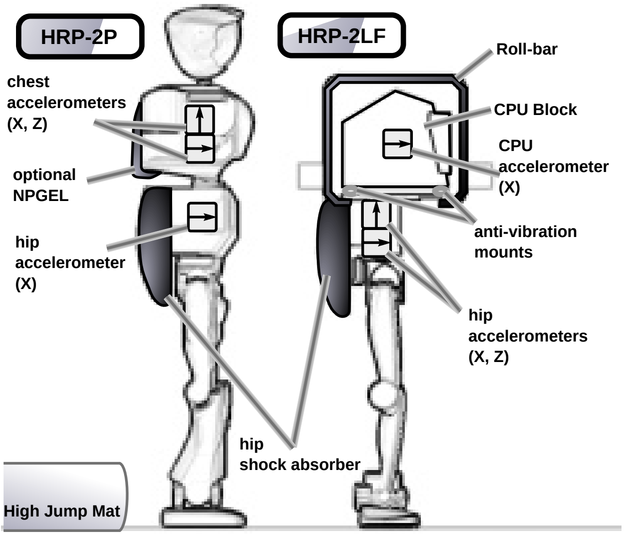


Fig. 4. Sensor and shock absorber layouts of HRP-2P and HRP-2LF

B. Falling over experiments with HRP-2LF

To avoid fatal damage to the robot, we proceeded carefully step-by-step. Before making the robot fall over on the floor directly, we experimented on the floor covered with $5[mm]$-thickness NPGEL sheets made by GELTEC.Co[9] and a high jump mat. NPGEL is an expanded Alpha GEL that is 0.2% compressive permanent set and $269.5[kPa]$ Young's modulus.

First, we laid the robot horizontally and confirmed that no problem arose. Next, we lifted it up by hand and let it fall from the leaning state several times. We were able to confirm that the computer didn't stop and the mechanism wasn't damaged. After this, we made the robot squat deeply from the STANDBY state, carried out the motion of leaning its body backwards slowly, and falls over. In all cases the computer neither stopped nor was the robot damaged.

Following the algorithm mentioned in Section 2, we generated the real time falling over motion. In this case we mainly tuned a parameter, the switching angle θ_1.

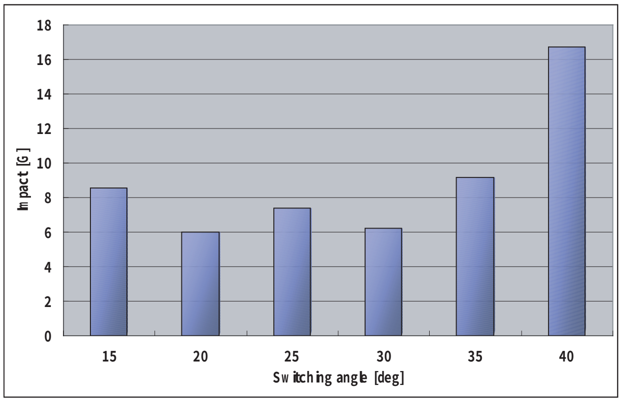


Fig. 5. Comparison of switching angle θ_1s with HRP-2LF

Figure 5 shows correlation between the maximum acceleration norm of hip accelerometers and switching angle θ_1. In this case eight sheets of NPGEL were laid over the floor. According to the graph, the impacts becomes smallest around the $\theta_1 = 20$[deg]. Afterward, we observed the change in impact force as we reduced number of mats.

Figure 6 compares five conditions i.e. high jump mat, eight NPGEL, three NPGEL, one NPGEL, and direct to floor. About 4.3[G] acceleration was observed in the experiment with high jump mat. We didn't adopt the floating structure of the computer block in HRP-2P. On the other hand, we adopted the tensioner because we found it effective to prevent electronic parts from dropping out.

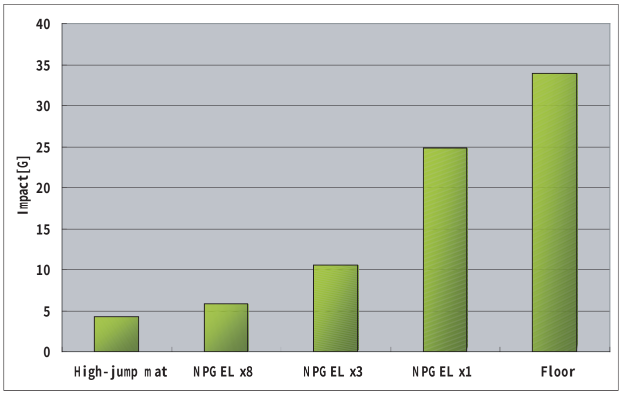


Fig. 6. Comparison of floor conditions with HRP-2LF

C. The experiments with HRP-2P

From the design stage of HRP-2P, we took into consideration the fact that it had to withstand falling over. Predesignated impact points of HRP-2P were equipped with large low-rebounding cushioning. Its back framework is constructed so that its inner mechanism is safe from direct damage when colliding with ground. However the ability to walk took first precedence. We also had little know how about falling over. Therefore there was no assurance that it can actually withstand a fall. So we decided to carry out falling over experiments one step at a time.

D. Test with light impact

To begin with, we made HRP-2P lie on the ground and confirmed that it wasn't damaged by its own weight.

Next, we fixed HRP-2P in a posture suitable for landing, and then pushed it down on the mat from leaned state. Testing several cases, we confirmed that it wasn't damaged by slight impact.

E. Test with heavy impact

From the result of the preliminary experiment with HRP-2LF, we can say that in the case of HRP-2P which has a similar physique to HRP-2LF, impacts of over 30[G] can be expected from actual fall. Here we directly made an impact on the robot body to confirm that it could actually withstand this. By confirming with controlled experiment, we can keep the damage at a minimum. HRP-2P differs from HRP-2LF by having waist joints, so we attached three acceleration sensors to the lower part of the body in the direction of X-axis, and the chest in the direction of X and Z-axis(Fig. 4). We used these accelerometers to compare impacts applied to the body.

We used the kick by a black belt master of KARATE as a source of impact(Fig. 7). This is a plain method because one can give a hit on any part at will and adjust the output power roughly. We tested thoroughly gradually increasing the impact. As a result, the computer of HRP-2P didn't stop when it got a similar acceleration to the falling over of HRP-2LF. But a plastic component connecting the hip cushion and frame was damaged. We dealt with this by structural reinforcement. Furthermore two wings of the cooling fan on the back were broken. The cause of this was considered to be the inner part of the exterior cover contacting with the fan. We exchanged the fan and shaved the inner part of the exterior cover's shape so as not to contact. From these results, we decided to keep maximum acceleration to 15[G].

F. The falling over experiment

We started the experiments with HRP-2P falling on a high jump mat. To determine θ_1, we tested three cases i.e. 25, 30 and 35 [deg]. Though there are few samples because of high risk of damage, we found that 25[deg] gave the best results. In this case, the maximum value of acceleration was about 4[G].

From the experiments with HRP-2LF, we can expect that the impact becomes 8 times as high as the case with

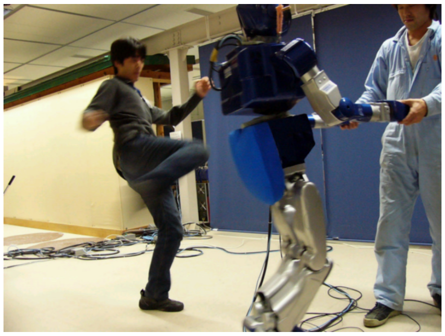


Fig. 7. Impact test of HRP-2P

the high jump mat when the robot falls over directly on the floor. This meant that an impact of over 30[G] can be expected. To keep the impact at a permissible range(about 15[G]), it was necessary to use at least two NPGEL sheets on the floor. As a safety margin, we attached four NPGEL sheets to the back of HRP-2P. This has the same effect as laying four NPGEL sheets on the floor.

As mentioned above, it became possible to keep the maximum impact to the frame at under 10[G] when HRP-2P falls directly to floor. *(see video)*

IV. THE EXPERIMENT OF FALLING OVER TO FLOOR WITH HRP-2P

Figure 8 shows the sequence of states when falling over. Figure 9 shows the values of the accelerometers, and Figure 10 the angles and the angular velocities of the pitch axes of its left crotch and left knee. States A to I in Figure 8 match the markers in Figures 9 and 10.

Figures 8-A to 8-B show the robot switching from STANDBY state to SQUATTING state. In the SQUATTING state(Fig. 8-B to 8-C) the joints are controlled at 60% of the maximum designed angular velocity. This margin was defined through experimentation. We also had to take into consideration the fact that there could be unexpected vibration from the robot actually hitting the ground. At the deepest part of the squat, the length of the legs was 45% of the length at STANDBY.

After θ reaches θ_1 the robot starts to extend its legs(Figs. 8-C through 8-E). Due to limitation in time and available torque, the legs were extended to 65% of the length at STANDBY. We used 25[deg] as θ_1. When θ reaches θ_2 the robot switches to TOUCHDOWN state. θ_2 is set at 3[deg] in this case.

At TOUCHDOWN(Fig. 8-F) the accelerometer mounted on the hip frame shows that the impact was around 4[G], shown as "Hip X" in Fig. 9.

After T_1 the robot switches to EXTEND2 and starts to extend its legs(Figs. 8-G to 8-H). Roll stops after the lower part of the back touches the ground. This is where the impact is highest. You can see in Fig. 9 that the "Chest X" accelerometer shows 10.5[G]. The sum of all the forces amounts to 11[G]. Without the NPGEL sheets added to the back the impact would be three times as high.

After T_2 the rolling stops and the robot goes to the FINISH state and prepares to get up(Fig. 8-I). In this case In this case $T_1 = 0.2$[sec] and $T_2 = 2.0$[sec].

Due to this falling over control, HRP-2P could remain operational without breaking down when it fell over to the floor. Figure 11 shows it getting up again after falling over. The method used to get up has been covered in [10]. HRP-2P can be operated without any cables by means of a wireless network and built-in battery. It can go through both falling over motion and standing up motion without any cables attached.

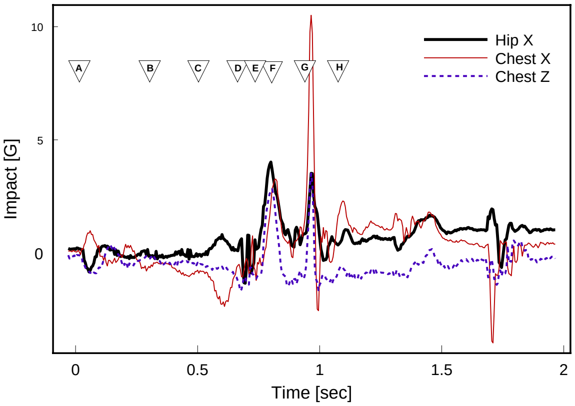


Fig. 9. Experiments: Falling impact of HRP-2P

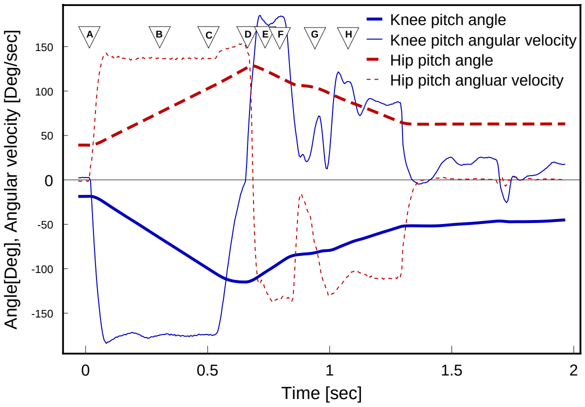
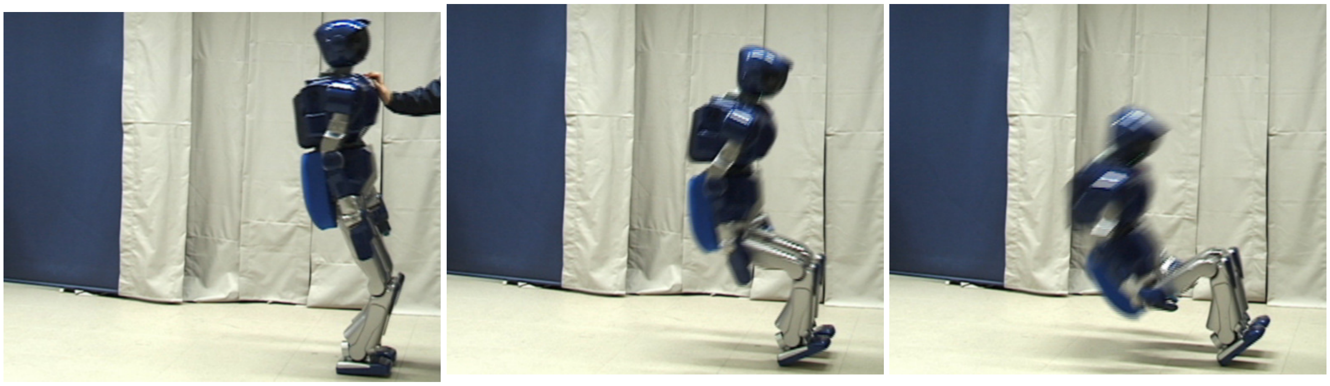


Fig. 10. Experiments: Falling motion of HRP-2P joints

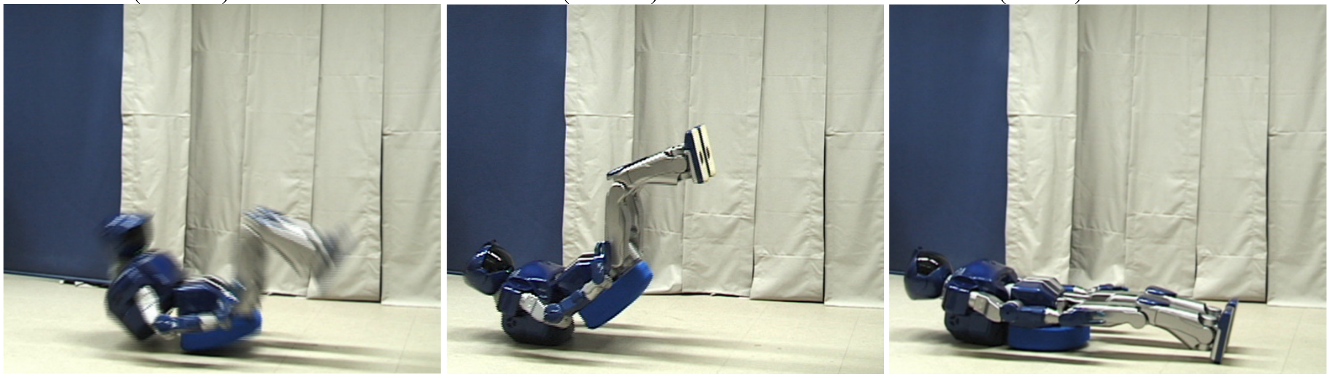
V. CONCLUSION

In this paper, we realized a human-sized humanoid robot that can fall over safely and stand-up again. The shock-absorbing structure of the HRP-2P was effective,



A(0sec) : Detect falling B(0.3sec) : Squatting down C(0.5sec) : Squatted

D(0.66sec) : Extend E(0.74sec) : Extended F(0.8sec) : Touchdown



G(0.94sec) : Rolling (Extend 2) H(1.1sec) : Rolled I(5sec) : Finish

Fig. 8. Experiments: Falling motion of HRP-2P

and the proposed falling over control algorithm successfully decreased landing impacts. We have shown that effective impact absorption is possible, even if the shock-absorbing structure does not cover the entire body. In the future, we plan to make a falling over controller, which can cope with more general situations.

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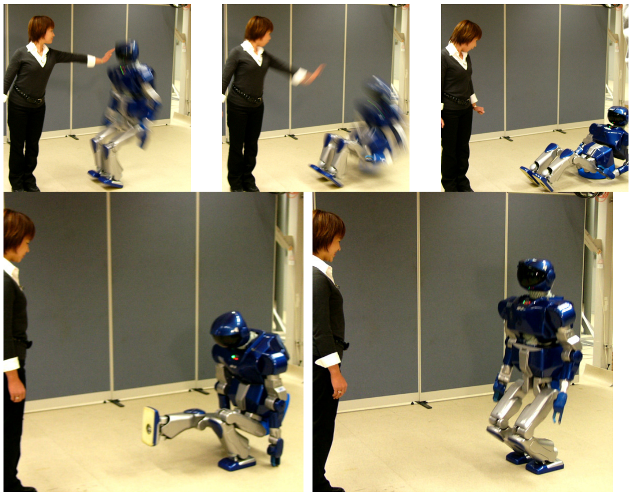

Fig. 11. Experiments: Falling over and standing up

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