Getting Back on Two Feet: Reliable Standing-up Routines for a Humanoid Robot

Jörg Stückler, Johannes Schwenk, and Sven Behnke
University of Freiburg, Computer Science Institute
Georges-Koehler-Allee 52, 79110 Freiburg, Germany

Abstract. To make bipedal locomotion robust, it is not sufficient to rely on postural responses that try to prevent falls, but it is also necessary to detect falls and to implement appropriate recovery procedures. This paper describes general methods for a humanoid robot to stand up from the prone and supine posture. We illustrate the use of these getting-up routines on the example of our robot Jupp. The proposed methods require only a limited number of degrees of freedom and observe common joint-angle limitations. We employed a physics-based robot simulation to analyze the kinematics and dynamics of getting up. The standing-up routines have been implemented on the real robot as well. Tests in our lab and at RoboCup 2005 showed that reliable standing-up is possible after a fall and that such recovery procedures greatly improve the overall robustness of bipedal locomotion.

Keywords. Getting up, standing up, humanoid robot

1. Introduction

Bipedal locomotion on a variety of surfaces under the influence of external disturbances is a challenging task for a humanoid robot. While many approaches exist to prevent the robot from falling, postural responses are frequently not sufficient to maintain an upright posture. If disturbances are large enough, a fall might become unavoidable. Falls are most likely in dynamic environments that contain other agents, such as humans, which interact physically with the robot. In the case of a fall, it is essential for the overall robustness to have reliable recovery procedures. The robot must be able to detect the fall, recognize its posture on the ground, and to get back into an upright posture.

While it is relatively easy to interpret the readings of attitude sensors in order to detect a fall and to decide, e.g. whether the robot lies in a prone (facing down) or a supine (facing up) posture, it is not straightforward to come up with reliable getting-up routines. This is due to the fact that the robot's center of mass (COM) projection to the ground leaves the convex hull spanned by the feet contact points. Hence, additional support points are needed in order to move the COM back into the foot polygon. Knees, elbows, hands, and the backside of the robot may be used to provide additional support. This results in whole-body motions with sequences of support points. The many degrees of freedom of humanoid robots and the changing contact points make it difficult to apply conventional motion-planning techniques. On the other hand, humans devised a variety of strategies to get up from the ground [1]. The observation of the human example served as inspiration for us during the development of getting-up motion sequences. However, compared to humans, humanoid robots often lack essential degrees of freedom, e.g. in the trunk. Furthermore, the robot joints are often restricted to a limited range of motion and can only provide limited torques. Humans overcome similar limitations by combining statically stable motion phases with dynamic phases.

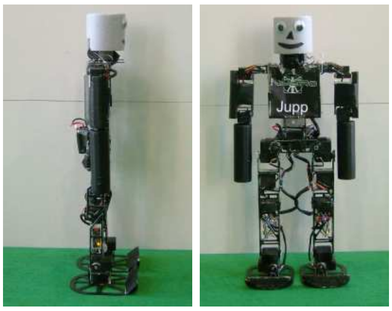
We follow this approach with the design of standing-up routines from the prone and supine posture. While statically stable motion sequences bring the COM projection close to the foot polygon, dynamic motion is needed to come back on two feet. Afterwards, statically stable motion brings the robot into an upright posture. We developed the standing-up routines using a physics-based simulation. This had the advantage that the stability of motion could be analyzed with perfect information about the robot dynamics on a variable time scale. We implemented the getting-up routines on two small humanoid robots, which were designed to compete in the RoboCup KidSize class. In order to assess the performance of these routines, we performed tests in our lab. We also used the behaviors during humanoid robot soccer games, which took place for the first time at RoboCup 2005 in Osaka, Japan.

The remainder of this paper is organized as follows: The next section reviews some of the related work. In Section 3, we detail the mechanical and electrical design of our small humanoid robot Jupp. We also introduce the framework we use for controlling its behavior. The main part of the paper is Section 4, where we explain in detail how the robot detects falls, recognizes its posture, and stands up from the ground. Experimental results are presented in Section 5.

2. Related Work

Very few humanoid robots are designed to survive a fall. Even the most advanced humanoids, like Asimo [2] and the Toyota Partner Robots [3], have not been demonstrated to be able to go to the ground nor to get back into an upright posture. They focus on walking stability. Indeed, only few humanoids are able to stand up. The best known example is HRP-2P (154cm, 58kg, 30DOF) [4], which has a lightweight backpack, strong arms, and wide ranges of motion in key joints. Kanehiro et al. proposed for it a motion controller that supports static motion and ZMP-controlled [5] dynamic motion. Standing-up after controlled going to the ground is performed by transitions between predefined states of contact between the robot's body parts and the surface. When the robot stands up from a prone position, the dynamic motion controller is applied to perform a short transition between kneeing and crouching. Dynamic motion is needed because the knees and soles of the robot can not have contact with the floor simultaneously. Kuniyoshi et al. [6] investigated the dynamics of standing-up from the supine posture by a roll-and-rise motion with humanoid robot K1 (150cm, 70kg, 46DOF). They analyzed the dynamics with a simplified model of the robot and explored the parameter space within the simulation. Whereas the simulated robot succeeded in standing-up, the motion was not transferable to the real robot. The authors explained this difference by the difficulty of simulating the contacts between robot and ground precisely.

Another humanoid that is able to get up from the ground is Sony's QRIO [7] (58cm, 7kg, 38DOF). It checks its position after a fall, turns face up, and recovers from a va-



Joint	Axis	Range (driven)	Range (relaxed)
Shoulder	roll	$0^\circ \leftrightarrow +180^\circ$	n/a
	pitch	$-90^\circ \leftrightarrow +90^\circ$	n/a
Elbow	pitch	$-45^\circ \leftrightarrow +135^\circ$	n/a
Spine	pitch	$-40^\circ \leftrightarrow +90^\circ$	$-45^\circ \leftrightarrow +90^\circ$
Hip	roll	$-40^\circ \leftrightarrow +90^\circ$	$-60^\circ \leftrightarrow +90^\circ$
	pitch	$-40^\circ \leftrightarrow +90^\circ$	$-60^\circ \leftrightarrow +90^\circ$
	yaw	$-90^\circ \leftrightarrow +90^\circ$	$-90^\circ \leftrightarrow +100^\circ$
Knee	pitch	$-130^\circ \leftrightarrow 0^\circ$	$-150^\circ \leftrightarrow +5^\circ$
Ankle	pitch	$-65^\circ \leftrightarrow +65^\circ$	$-80^\circ \leftrightarrow +80^\circ$
	roll	$-90^\circ \leftrightarrow +30^\circ$	$-90^\circ \leftrightarrow +30^\circ$

Figure 1. Lateral and sagittal view of our robot Jupp. The table shows the range of motion for its joints.

riety of prone positions by static movements. There is a variety of smaller servo-driven humanoid robots, which have been designed for the RoboOne competitions [8], where robot fighters engage in martial arts and standing-up is an essential feature. The CycloidII robot by Robotis [9] (41.5cm, 2.4kg, 23DOF), for example, had some success in these competitions. It is capable of standing up statically from both the prone and supine posture due to its powerful Dynamixel actuators and disproportional long arms. Kondo also constructed their popular KHR-1 [10] robot (34cm, 1.2kg, 17DOF) for the RoboOne competitions. Static standing-up routines from both lying postures have been implemented for it. Robotic soccer is another domain where standing up is important. At RoboCup 2005 [11], Team Osaka [12] demonstrated static standing-up of their robot VisiON Nexta (47.5cm, 3.2kg, 23DOF) from each posture. This robot has yaw and pitch waist joints and is driven by Dynamixel actuators.

3. KidSize Humanoid Robot

Hardware Design: Fig. 1 shows two views of our humanoid robot Jupp. It has been designed for the 2005 RoboCup Humanoid League competitions in the KidSize class. As can be seen, Jupp has human-like proportions. Its mechanical design focused on weight reduction. Jupp is 60cm tall and has a total weight of only 2.3kg. The skeleton of the robot is mostly constructed from aluminum extrusions with rectangular tube cross section. We removed all material not necessary for stability. Jupp's feet and its forearms are made from sheets of carbon composite material. The forearms are bendable in sagittal direction and are covered by a lightweight foam tube.

The robot is driven by 19 servo motors: 6 per leg, 3 in each arm, and one in the trunk. Three orthogonal servos constitute the hip joint, two orthogonal servos form the ankle joint, and one servo drives the knee joint. We selected the S9152 servos from Futaba to drive 2 DOFs of the hips, the knees, and the ankles. These digital servos are rated for a torque of 200Ncm, and can be driven to positions of $\pm 65^\circ$. They have a weight of only 85g. The hip yaw joints need less torque. They are powered by DS 8811 digital servos (190Ncm, 66g, $\pm 90^\circ$). Jupp's arms do not need to be as strong as the legs. They are powered by SES640 analog servos (64Ncm, 28g, $\pm 90^\circ$). Two orthogonal servos constitute the shoulder joint and one servo drives the elbow joint. We use the following definition of rotational directions: Positive pitch bends in on the frontal side of the robot. Positive roll and yaw means rotating outwards looking forward. The table in Fig. 1 lists the range of motion for all joints.

Jupp is fully autonomous. It is powered by high-current Lithium-polymer rechargeable batteries, which are located in its lower back. The servos are interfaced to three tiny ChipS12 microcontroller boards. One of these boards is located in each shank and one board is hidden in the chest. Every 12ms, target positions for the servos are sent from the main computer to the ChipS12 boards, which generate intermediate targets at 180Hz. This yields smooth joint movements. The microcontrollers send preprocessed sensor readings back. In addition to joint potentiometers, Jupp is equipped with an attitude sensor. The attitude sensor is located in the upper trunk. It consists of a dual-axis accelerometer and two gyroscopes. We use a Pocket PC as main computer [13], which is located in Jupp's chest (see Fig. 1). This computer runs behavior control, computer vision, and wireless communication.

Behavior Control: We control Jupp using a framework that supports a hierarchy of reactive behaviors [14]. This framework allows for structured behavior engineering. Multiple layers that run on different time scales contain behaviors of different complexity. For Jupp we use three levels of this hierarchy: individual joint, body part, and entire robot. This structure restricts interactions between the system variables and thus reduces the complexity of behavior engineering.

The lowest level of this hierarchy, the control loop within the servo, has been implemented by the servo manufacturer. It runs at about 300Hz for the digital servos. We monitor target positions, actual positions, and motor duties. At the next layer, we generate target positions for the individual joints of a body-part at a rate of 83.3Hz.

Simulation: In order to be able to design behaviors without access to the real hardware, we implemented a simulation for Jupp, which is based on the Open Dynamics Engine [15]. The simulation allows examining the robot's behavior on variable time scales. This helps the behavior engineers to design complex or dynamic motions.

4. Standing-Up Routines

A standing-up routine is triggered when the robot has fallen over with high certainty. To determine this state the attitude sensors are interpreted. If the robot is tilted more than 45° for more than one second, we assume that the robot has fallen. As our robots cannot lie other than facing upwards or downwards on a flat surface, we only have to inspect the sign of the sagittal tilt in order to recognize its posture.

Assumptions: We developed standing-up routines for the RoboCup Soccer domain from the supine and prone posture under the following assumptions:

- The surface is flat carpet (soft, moderate friction).
- No obstacles conflict with the robot's motion during the standing-up routine.
- The robot is lying straight on the surface with all joints moved to zero positions.

Motion Generation: The standing-up motions are generated by setting target positions for individual joints. We use sinusoidal trajectories, which are smooth and natural for static movements, whereas for dynamic motions the distinctive points of target velocity and acceleration being zero or maximal are obtained easily from the waveform itself.

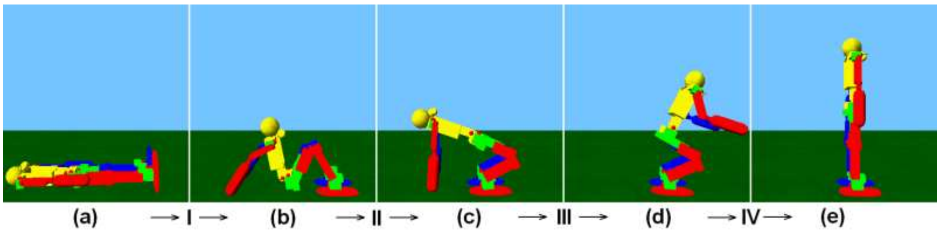


Figure 2. (a)-(e) Starting and end positions of phases I-IV when standing up from the supine posture.

Standing up from the Supine Posture: Standing up from the supine posture in a statically stable way can be achieved by folding the body over the feet supported by the arms. In this movement the knees and the ankle pitch joints are bent in. Then, the hip pitch joints are moved positively and the trunk is leaned back by rotating the spine negatively to shift the COM over the feet. Now, the trunk is brought over the feet by bending in the spine in positive direction and, finally, the whole body is straightened.

Jupp's limitation of the ankle pitch, knee and spine joint motion ranges complicates this motion, because the arms are not long enough to support the motion while the hip pitch joints and the spine let the COM shift over the feet. Instead, the body has to be swung forward, while the arms lose contact with the surface. During this dynamic movement, the robot tips over the trailing edges of the feet, which form the support polygon. The COM projection onto the surface is moving from behind the trailing edges of the feet to the front until the whole feet are standing on the surface. The standing-up motion unfolds as four separate phases (see Fig. 2).

Phase I. Move the upper body into a sit-up posture and move the arms into a supporting position behind the back.

Phase II. Move into a bridge-like position using the arms as support.

Phase III. Move the COM over the feet by swinging the upper body to the front.

Phase IV. Move the body into an upright posture.

During Phases I and II the robot moves into an advantageous, bridge-like starting position for Phase III. To be able to bend the trunk in, the arms are angled by rotating the elbow and shoulder pitch joints. Additionally, the shoulder roll joints are moved to enlarge the distance of the elbows to the ground by moving the arms outwards. Now, the robot can sit up. The ankle pitch joints are rotated such that the feet lie flat on the surface, while the hip and the spine pitch joints are bent in. Meanwhile, the elbow has to be rotated further to prevent the forearms from touching the ground. As soon as possible, the elbows start moving back to straighten the arms, while the shoulder pitch joints are rotated further into negative direction. The shoulder roll joints are moved back to zero. This brings the arms into a backward position, which will support the later bridge-like position. During the alignment of the arms, when the hip pitch joints and the spine have reached their target positions, the legs are bent in by folding the knees to their negative limit. The twist of the hip is compensated by rotating the spine further, such that the robot remains sit-up. In Phase II, the arms are straightened in the elbows, and the hip pitch and spine joints are moved to zero, such that the hip is lifted. The ankle pitch joints rotate positively to let the hip and the knees shift forward.

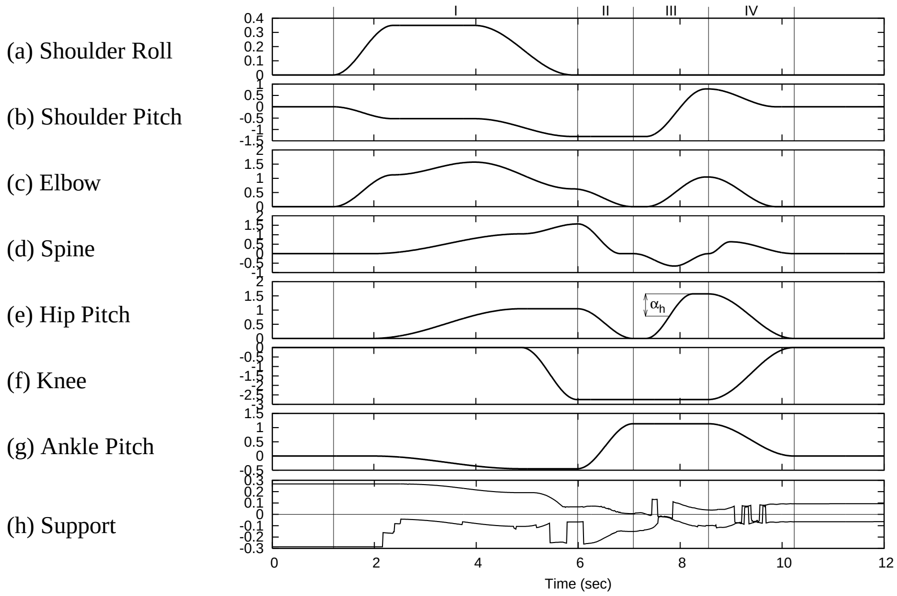


Figure 3. (a)-(g) Target positions (in rad) of individual joints when standing up from the supine posture ($\alpha_h = 0.25\pi$). (h) Distance (in m) of the COM projection to the extreme points of the support polygon in sagittal direction.

Now, the COM projection can be shifted close to the trailing edges of the feet in Phase III by rotating the hip pitch joints in positive direction, while the spine joint is moved negatively. As soon as the robot begins to tip back over the trailing edges of the feet, as the arms are not long enough, the arms are swung forward and the spine is rotated positively to accelerate the trunk forward. As the arms lose contact with the ground, the COM projection moves out of the support polygon until the whole foot soles are touching the ground again (see Fig. 3(h)). We identified the main control parameters to be the amplitude of the hip pitch joint trajectory, α_h, and the length of the dynamic phase. Both values directly influence the speed of the trunk forward motion. Too low values let it cease before the COM has moved over the feet, whereas too high values increase the chance of the body to overshoot and to fall over the leading edges of the feet.

Finally, all joints are brought back to zero to get the robot into an upright posture. The spine is temporarily bent in to stabilize the motion. Fig. 3(a)-(g) show details on the trajectories and their exact timing.

Standing up from the Prone Posture: The main problem of standing up from the prone posture is that the knees of a humanoid robot cannot be bent in positive direction. If it was possible, standing up from the prone posture would be similar to standing up from the supine posture. Instead, the COM projection has to be brought near to the feet by first bending in the ankles, the knees, the hip, and the spine maximally, such that the robot touches the ground with the knees and the leading edges of the feet. Then, the arms can be utilized to tip over the leading edges of the feet and to let the COM, that is situated in the hip region, be shifted over the feet. This motion is dynamic, as the COM projection leaves the support polygon at the leading edges of the feet.

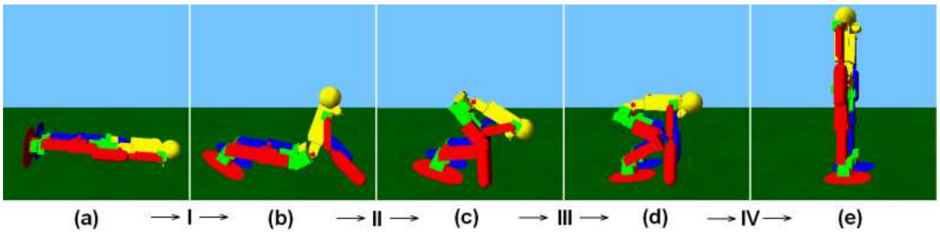


Figure 4. (a)-(e) Starting and end positions of phases I-IV when standing up from the prone posture.

The mechanical limitations of Jupp, especially the limited joint angle ranges in the knees and the ankles, complicate the standing-up motion, as the legs can not be fold in completely. Thus, the arms have to lift a longer lever, which is formed by the leading edges of the feet and the COM. For a detailed description of the motion sequence, we divide it into four phases.

Phase I. Lift the trunk and bring the forearms under the shoulders.

Phase II. Move the COM projection as close as possible to the leading edges of the feet by bending in the spine, the hip pitch and the knee joints.

Phase III. Straighten the arms to let the robot tip over the leading edges of the feet.

Phase IV. Bring the body into an upright posture.

As indicated by Fig. 4(c)-(d), the soles have to be moved as even as possible onto the ground, such that the dynamic motion is short. Therefore, the ankle pitch joints are rotated to their maximum position. To support this movement, the feet are lifted from the ground by bending in the knee and the hip pitch joints to let the knees contact the surface instead of the feet. Jupp cannot bend in the arms enough to get the ends of the forearms below the shoulders, while the trunk is lying straight on the surface. Thus, it prepares to support the lifting of the trunk with the arms: The elbows are bent in and the shoulder pitch joints are moved back, such that the endpoints of the forearms are still on the lateral plane of the robot. Meanwhile, the arms are rotated outwards in the shoulder roll joints, as they can be moved back to get the forarms below the shoulders when the trunk is lifted up. The trunk lifting is accomplished by bending out the spine and hip pitch joints. The arms support the motion by pressing the forearms onto the ground, as the elbow joints are straightened partly and the shoulder pitch joints move back to zero. During this motion, the arms can be brought under the trunk by moving the shoulder roll joints back to zero. Finally in this phase, the elbows are straightened further and the flexible forearms are strained by the weight of the trunk.

In Phase II, the spine, the hip pitch joints, and the knees are fold in, bringing the COM projection close to the leading edges of the feet. The arms support this movement by rotating the shoulder pitch and elbow joints in positive direction. Now, the robot is holding a bridge-like position, leaning on the leading edges of the feet and the strained forearms.

To let the body tip over the leading edges of the feet in Phase III, the shoulder pitch joints have to be rotated further to the $+90°$ position and the arms are straightened by the elbow joints. The COM projection is leaving the support polygon shortly behind the leading edges of the feet, as described before and shown in Fig. 5(h). The amplitude of the elbow trajectory, α_e, and the length of the dynamic phase are the main control

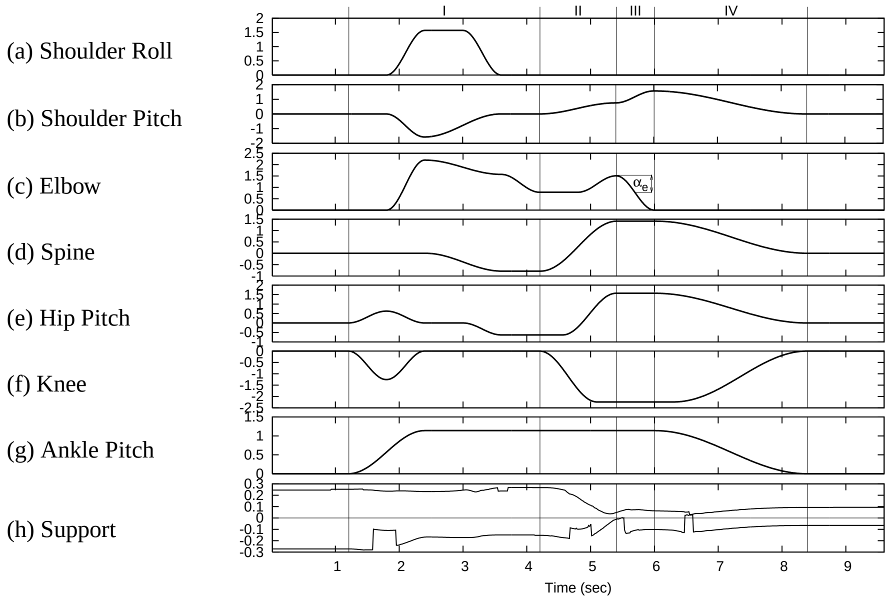


Figure 5. (a)-(g) Target positions (in rad) of individual joints when standing up from the prone posture ($\alpha_e = 0.24\pi$). (h) Distance (in m) of the COM projection to the extreme points of the support polygon in sagittal direction.

parameters for the dynamic motion. If they are too small, the COM projection will not leave the support polygon. Too high values cause the backward motion to overshoot, such that the arms are thrown back and are not able to absorb the following forward motion, which causes the robot to fall over the leading edges of the feet again.

During the final Phase IV, all joints are moved to their zero position to bring the body into an upright posture. Fig. 5(a)-(g) show details on the trajectories and their exact timing.

5. Experimental Results

We designed the proposed routines using the simulation and transfered them to the real hardware. We performed extensive tests in our lab. Under normal circumstances, i.e. appropriate battery voltage, the routines worked very reliably at high success rates of 100 percent in 100 tests.

We observed, that the main control parameters α_h and α_e can be chosen from a wide range of values, still yielding highly reliable standing-up routines (e.g. $\alpha_h = 0.21\pi \pm 0.025\pi$, and $\alpha_e = 0.16\pi \pm 0.06\pi$). This is explained by the shortness of the dynamic phases, which is achieved by moving the COM projection as close as possible to the foot polygon in the preliminary static phases. Fig. 6 and Fig. 7 show image sequences of the dynamic phases of standing up from the supine and prone posture, respectively.

The standing-up routines proved to be robust against changes in the initial posture and varying servo temperatures. When standing up from the prone posture, low battery voltage causes the supply voltage of the arm servos to break down during the high load in the dynamic phase. Although the routines have been developed based on rather restrictive

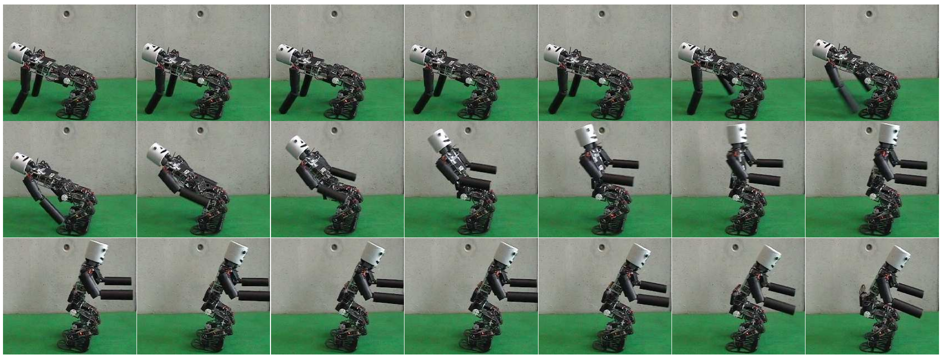


Figure 6. Image sequence showing dynamic Phase III of standing up from the supine posture ($\alpha_h = 0.235\pi$).

assumptions, the generated motions proved to be robust against relaxation of each of the assumptions. For example, the robot can also stand up on hard and slippery surfaces like stone or hardwood. The getting-up routines even worked when the joints of one arm were relaxed.

The routines did not only work in our lab, but were used during soccer games at RoboCup 2005. In this dynamic environment, multiple robots are in pursuit of the ball, which leads to unavoidable body contact. The physical interaction of the robots disturbs the walking pattern, which may lead to falls. Because human help during play is not allowed, the robots must be able to get back into an upright posture by themselves. Our robots were able to detect falls reliably, triggered the appropriate standing-up routine, and succeeded almost always in standing up. Because the robots continued play afterwards, this greatly improved the overall robustness of our soccer team.

6. Conclusions

In this paper, we proposed general methods for standing up with a humanoid robot from both the prone and the supine posture. In order to overcome hardware limitations, such as limited range of motion or torque limits, we combined statically stable motion phases with dynamic phases. Statically stable motion sequences that utilize support by the arms, the knees, or the backside of the robot bring the COM projection close to the foot polygon. Dynamic motion is needed to come back on two feet. Afterwards, statically stable motion brings the robot into an upright posture.

We designed the standing-up routines using a physics-based simulation and implemented them on two small humanoid robots, which were designed to compete in the RoboCup KidSize class. The routines worked very reliably in our lab. Furthermore, they were integrated into the behavior control software that was used during 2 vs. 2 soccer games at RoboCup 2005. Because unavoidable robot interactions in this dynamic environment lead to falls, the reliable standing up was one of the key factors that determined the performance of our soccer team. Our team NimbRo played well. The getting-up was appreciated by the crowds. We reached the final in the soccer games, against the titleholder, Team Osaka. The exciting game ended 2:1 for Osaka. Videos showing the standing-up routines and their use in the RoboCup competition can be downloaded from our webpage http://www.NimbRo.net/media.html.

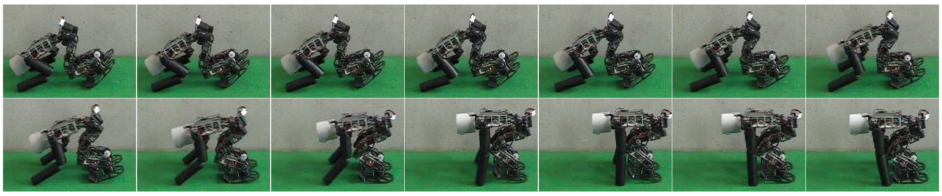


Figure 7. Image sequence showing dynamic Phase III of standing up from the prone posture ($\alpha_e = 0.22\pi$).

We plan to work into two directions in the future: avoiding falls and minimizing the damage of a fall. To avoid falls, we will implement various postural responses, based on sensory feedback. To minimize damage, we plan to bring the robot into a protective posture and to relax some of its joints prior to ground contact.

Acknowledgements

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