Mechanical Challenges for Further Humanoid Robot Evolution

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Abstract

In this paper, we develop two noble mechanisms for improving the motions of humanoid robots. The double spherical joint is a six DOF joint that consists of six single DOF mechanical pairs in series with their axes intersecting at a point. The double spherical joint replaces two hip joints (six DOF) of humanoid robot, and even provides the equivalent function of waist joints without actually adding them. The backlash clutch is a new joint drive mechanism and to be used in this paper for knee joints of humanoid robots. The backlash clutch enables switching between drive and free modes. The free mode will play a role in emerging humanoid behaviors that are dynamically coupled with the environments. A humanoid robot is under development being equipped with the two mechanisms. Results of preliminary experiments are to be shown.

Keywords: Humanoid robots, Biped walk, Hip joints, Knee joints, Mechanisms

1 Introduction

Research of humanoid robots extends from mechatronics integration, motion control, sensing and perception, toward experimental exploration of developmental theories of the communication, the symbol grounding, the sense of self, the binding problem of multimodal sensations, and the intention and mind. Such exploration is challenging not only from the engineering view point of building intelligent machines, but also from the scientific view point of understanding the human, and therefore it is open ended.

The body of humanoid robot is already a large-scale system with, roughly speaking, 30 motors, 50 sensors, and quite a few processors. The mechanical design of humanoid robots has focused on integrating all the mechatronic components in a limited space of human shaped body. The reported models of humanoid robot [1]~[6] clearly show the success of the mechanical design. The issue of artistic design is illuminated more recently. However, the authors claim that ever developing research of humanoid robots also demands the evolution of body mechanisms.

The evolution of actuators, materials, and batteries will significantly change the mechanical design of humanoid robots in the future. In this paper, we rather focus ourselves and discuss the driving mechanisms of joints. The specific problems raised in this paper are:

1. Joint allocation design that maximizes the whole body mobility of humanoid robots.
2. Joint transmission design that switches between the drive and free modes.

The mobility is improved by simply introducing more joints and actuators, though it requires further and harder challenge of integration. Especially, for walking mobility, the recent design of humanoid robots tends to include waist joints, which are important both for human like mobility and for stability control of biped walk using the upper body. The humanoid robot without a waist roll-joint has to bend the knees to maintain the manipulability of the COG (center of gravity) in the horizontal direction in the frontal plane.

In this paper, we propose to have two hip joints at a point. A hip joint here is a virtual joint and indicates a point where the first three joints axes of a leg intersect like a spherical hip joint of the human. Therefore, we suggest having a point where six joint axes, namely first three of both legs, share a point of intersection. We designed and fabricated such a drive mechanism and named the double spherical joint. With the double spherical joint, a humanoid robot obtains an equivalent mobility that a waist roll-joint and a waist yaw-joint could provide, without actually having them. Therefore, the double spherical joint guarantees full manipulability of the COG in the horizontal plane being independent to the leg configuration.

The current design of transmission of humanoid robots is not prepared to discuss dynamical coupling between the humanoid body and the environments. The natural human motion that we see in an elegant walk or in fine dancing is acquired through the coupling. The rehabilitation of human sometimes starts from laying himself down on the floor to feel the gravitation or lean himself against the wall to remove the fear. Clearly, feeling the gravity and the environmental constraints not only with a specific sensor like vision but with the whole body suggests a design principle of sensory motor system of intelligent machines. Natural motions of humanoid robots may not be obtained from just imitating human motions. They would be acquired through the dynamics of their body and the environments including the gravitation. The passive walk of McGeer [7] [8] opened an interesting and suggestive approach to this problem.

In this paper, we also propose a joint drive mechanism that can switch between drive and free modes. When the backlash clutch cuts mechanical transmission from the motor to the joint, the joint behaves like a free joint. The joint motion in the free mode is transparent and determined purely by the environmental forces and constraints. In the drive mode, on the other hand, the backlash clutch engages the motor with the joint and transmits large forces. Conventional clutch mechanisms either weigh heavy or transmit insufficient forces. The backlash clutch solved the problem adopting a simple mechanism and a control algorithm. The backlash clutch is integrated in the knee mechanism of a humanoid robot.

A humanoid robot is under development adopting both the double spherical joint as the hip joints and the backlash clutch as the knee joints. The preliminary results of experiments are to be shown in this paper to discuss the effectiveness.

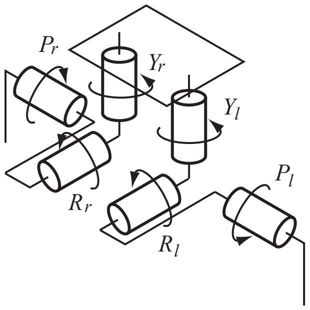

Figure 1: Conventional hip joints

2 The Double Spherical Hip Joint

Figure 1 shows a conventional mechanical design of hip joints. The figure includes the both hip joints where Y_l, R_l, and P_l are yaw, roll, and pitch joints of the left leg and Y_r, R_r, and P_r are those of the right leg. The three joints of each leg have axes intersecting at a common point, which is called a hip joint since the three joints are functionally equivalent to a spherical hip joint of the human.

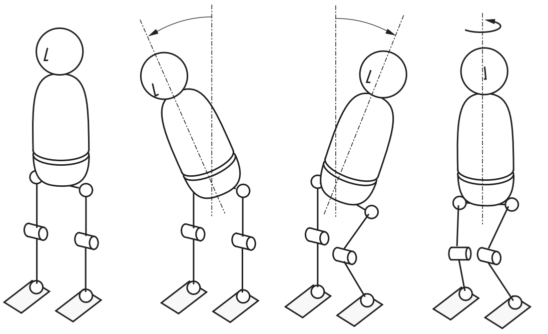

Figure 2: Hip and knee joint motions required to control upper body

Figure 2 shows the motions of hip and knee joints when the upper body is required to incline itself. The pitch and roll inclinations of the upper body are used to control the COG of the whole body. It provides an effective feedback control law for stabilizing the biped walk. Note that the pitch motion is always available even when the knee joints are stretched. On the other hand, the roll motion is degenerated when the knees are stretched.

This is why most current humanoid robots have to bend the knees more or less. The yaw motion of the upper body is not effective for stabilization, but is still useful as body mobility. A finite yaw motion also needs to bend the knees. Biped walk with the knees bent does not look like natural walk, and even wastes energy that could be saved if the knees were stretched.

A solution to provide manipulability of the COG is to add a few degrees of freedom as waist joints. It would, however, increase the weight and complexity of mechanism.

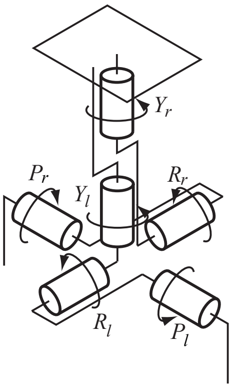

Figure 3: Double spherical joint

Figure 3 shows the double spherical joint. This mechanism has same six degrees of freedom as the conventional design shown in Figure 1. All six joint axes are intersecting at the center point. In other words, the distance between the two hip joints is set zero for the double spherical joint.

Figure 4 shows that for a humanoid robot with the double spherical hip joint the roll and even yaw motions are available independent to whether the knees are bent or not. This mechanical design implies that the mobility of three degrees of freedom of waist joints for rotating the upper body can be realized without actually adding waist mechanisms but adopting the double spherical joint as the hip joints.

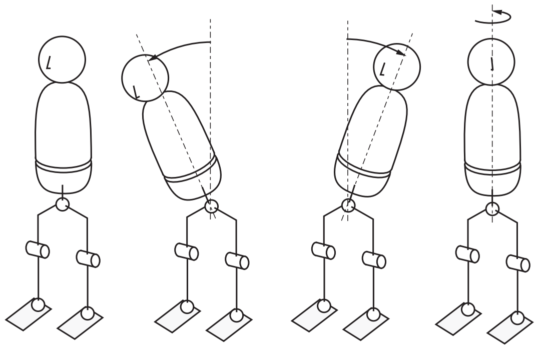

Figure 4: With the double sperical joint, full manipulability of upper body is available independent to the leg configuration

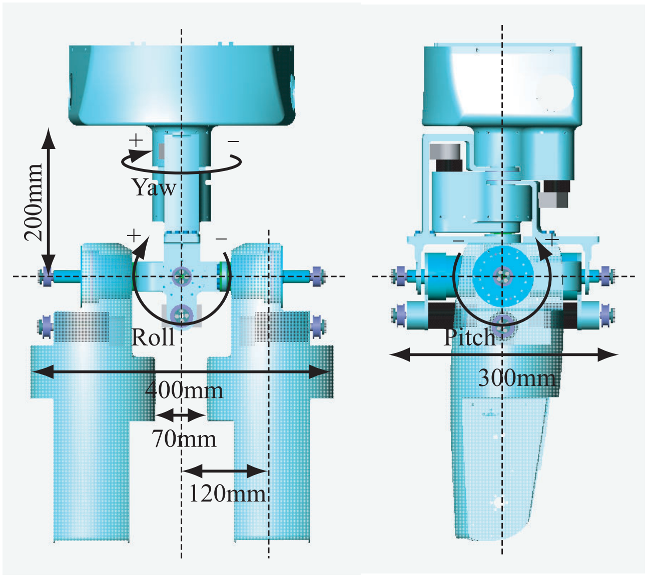

Figure 5: Dimensions of the designed double spherical hip joint

The dimensions of the designed double spherical hip joint is illustrated in Figure 5. It has been the major design issue to accommodate a large workspace and to maintain high mechanical stiffness. Figure 6 shows a photograph of the developed. For yaw and roll joints, 90[W] DC servomotors and 1:100 Harmonic drives gears are used. For pitch joints, 150[W] DC servomotors and 1:100 Harmonic drives gears are adopted.

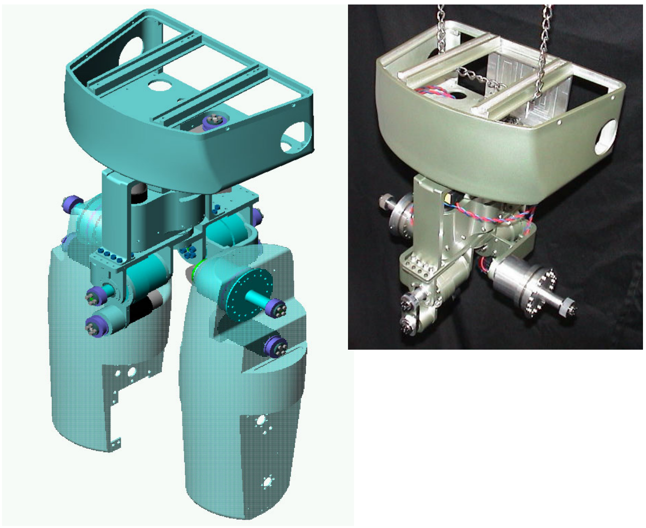

Figure 6: Photo of the double spherical hip joint

The workspace of the developed double spherical hip joint is shown in Table 1. For comparison, the motion ranges of typical human joints are also included in the table. The double spherical hip joint has a smaller motion range for the backward bending of the thigh than that of the human. The motion ranges of the double spherical joint in the other motions are nearly as large as those of the human.

Table 1: Workspace of double spherical hip joints

	Double spherical joint	Human
Yaw	-35∼35[degree]	-35∼35[degree]
Roll	-50∼50[degree]	-20∼35[degree]
Pitch	-120∼30[degree]	-135∼90[degree]

3 Knee Joints with the Backlash Clutch

3.1 Gravity Compliant Motions and Mechanisms

An intelligence of machines would be seen if they could acquire by themselves appropriate motions that their body accepts. The passive walk proposed by McGeer [7, 8] showed that the passive dynamics of mechanism involves in itself the foundation of walking motion pattern. More surprisingly, the passive walk patterns in his video looked natural and even noble like those of animals. In our daily life, we learn sports and motion patterns by moving our body according to reference patterns and modifying them to fit ourselves. We may acquire such a motion by making the inertia and gravity force that is generated by the motion or generates the motion more comfortable to our body. To study the principle of intelligence for dynamic motion acquisition, a humanoid robot would need a body that is compliant to the inertia and gravity force.

It is also interesting why the passive walk looks natural to us. It would not be surprising that free joint motions are the most acceptable to our body, and that we feel them comfortable and therefore natural. If it explains the case, developing natural looking motions for humanoid robots should focus on utilizing passive motions.

Based upon the above motivations we study the joint drive mechanism that can switch between drive and free modes.

3.2 The Backlash Clutch

Figure 7 shows the principle of the backlash clutch. The mechanism is composed of three components. Part a is rotated by a motor and fixed neither to upper link A nor to lower link B. Part b is fixed to lower link B. There is a backlash between Part a and Part b. If the backlash is set zero, them the torque of motor is directly transmitted to B through a and b. We set the backlash an appropriate nonzero value. We measure the both rotations of Part a and Part b. If we control the motor and Part a so that Part a does not touch Part b, then free motion is actively realized. It is the free mode.

Switching to the drive mode, Part a is first controlled to make a surface contact with Part b, and then transmits an arbitrary driving force. Therefore, there is a slight time delay before actually transmitting driving force. The time delay should be minimized since it becomes critical when the driving force alternates its directions repeatedly and rapidly.

However, since the humanoid robot as well as the human lives in the gravity field, Part b usually pushes Part a in one direction due to the gravitation. Therefore, the motor can immediately transmit torques as much as the gravitation torque in the both directions. More precisely, it can transmit arbitrary torque in the pushing direction, and torque as much as or less than the gravitation torque in the pulling direction.

Mechanical components of the backlash clutch are shown in Figure 8. Parts a and b in the figure corresponds to those of Figure 7. Rubber material is used in the backlash to absorb excess collision forces.

3.3 Backlash Clutch in the Knee Joints

Figure 9 shows the design of the knee joints with the backlash clutch. The knee joint uses a 150[W] DC servomotor and a 1:100 Harmonic drives gear. The rotation angle of Part a is θ in Figure 7. θ is measured by a motor encoder. The rotation angle of Part b is represented by ϕ. ϕ is measured by an additional encoder.

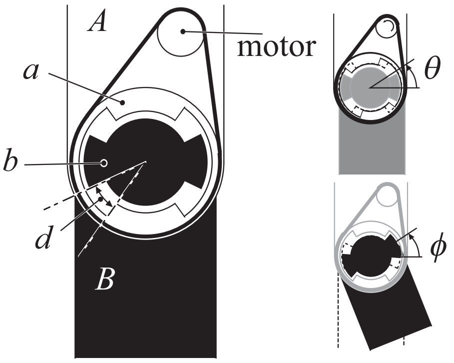

Figure 7: Principle of the backlash clutch

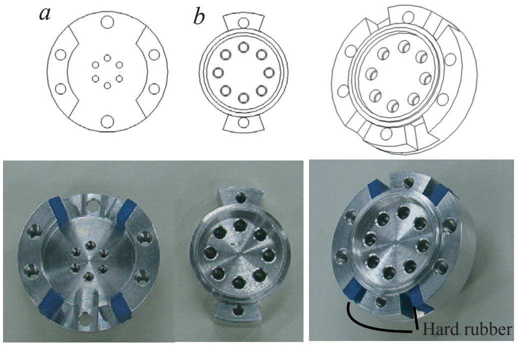

Figure 8: Components of the backlash clutch

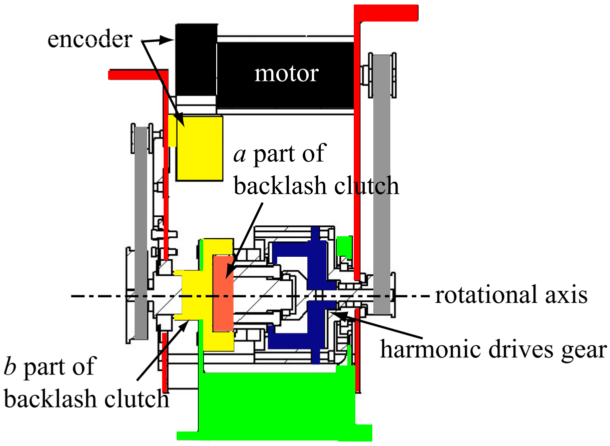

Figure 9: Design of the knee joint

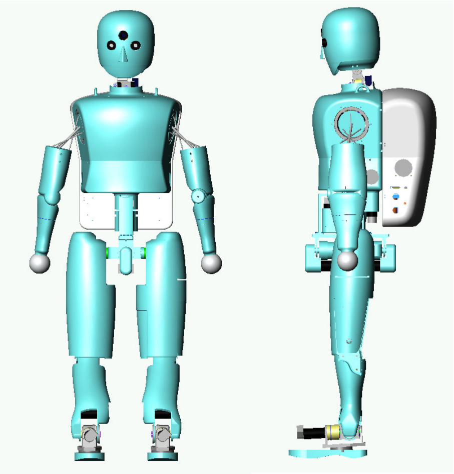

Figure 10: The CREST humanoid robot

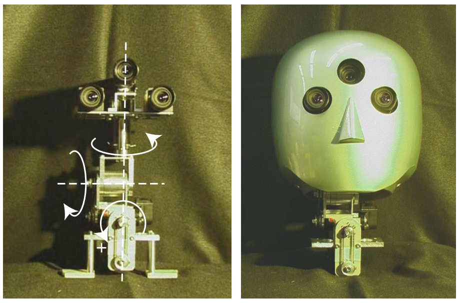

Figure 11: Head and neck mechanism

Figure 12: Cybernetic shoulder mechanism

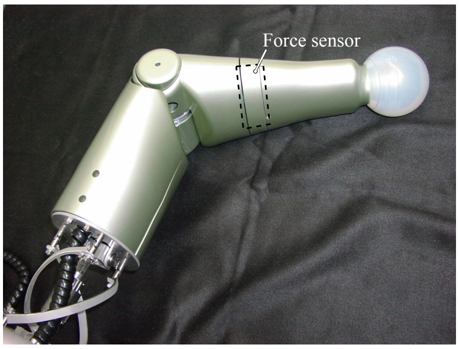

Figure 13: Elbow mechanism

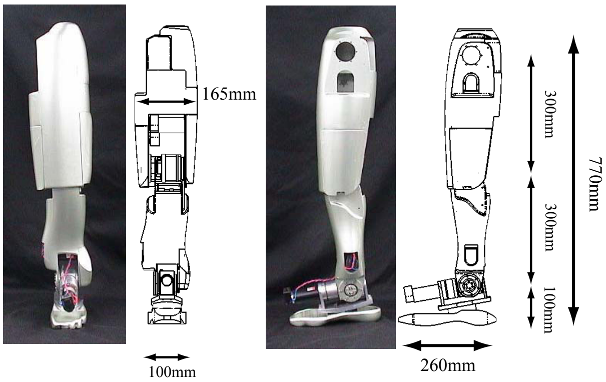

Figure 14: Leg mechanism and its dimensions

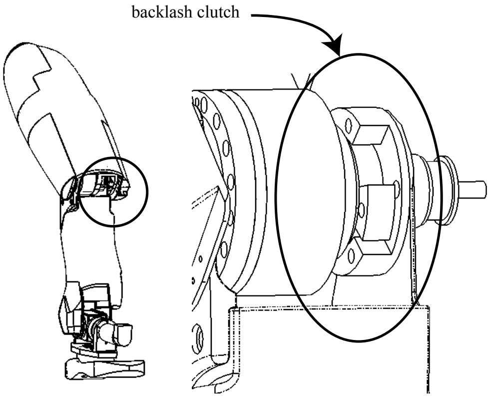

Figure 15: Integrating the backlash clutch

4 The CREST Humanoid Robot

We designed a humanoid robot adopting the double spherical hip joint and the knee joints with the backlash clutch. Figure 10 shows the illustration of the humanoid robot. It is 150[cm] in height and estimated to weigh approximately 60[kg].

The head and the neck mechanism are shown in Figure 11. The neck has three degrees of freedom. The head is equipped with two monochrome progressive scan cameras and an NTSC color camera.

The chest and shoulder part is shown in Figure 12. The cybernetic shoulder [9] has advantages of the large workspace and the human like motion. The cybernetic shoulder is slightly modified to fit in the chest. It has three degrees of freedom each. The inertial sensors such as gyro sensors and accelerometers are also integrated in the chest.

Figure 13 shows the elbow mechanism of one degree of freedom. A six axes force sensor is equipped.

The leg mechanism and its dimensions are represented by Figure 14. Each leg has six degrees of freedom, namely, one degree of freedom as a knee joint, two degrees of freedom as ankle joints, and three degrees of freedom of a hip joint. The backlash clutch is implemented as seen in Figure 15. A six axes force sensor is also equipped on the foot.

The main structural parts of body made by magnesium alloy casting for pursuing both lightweight and high mechanical stiffness.

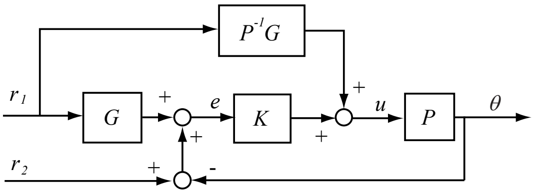

Figure 16: Two DOF control system

5 Control Algorithm of the Backlash Clutch

5.1 Two DOF Control for Mode Switching

We propose a control algorithm of the backlash clutch. The backlash clutch needs the following three control modes: (1) free mode, (2) drive mode, and (3) transition mode between free and drive modes.

To realize the above three control modes, we adopted a two DOF control system as shown in Figure 16, where P denotes the transfer function of motor and gear, K means the feedback controller, G indicates the transfer function that describes the desirable response of θ, and finally r_1, r_2 are reference signals.

The transfer function G is designed not to have zeros, since the response of θ should have no over shoot with the high gain feedback K. The transfer function G must have an identity steady gain.

Reference signals r_1, r_2 are selected differently according to the control mode as follows:

(1) Free mode $r_1 = 0, \quad r_2 = \phi$
θ is controlled to follow ϕ maintaining the distance between Part a and Part b of Figure 7.

(2) Drive mode $r_1 = \phi_{ref}, \quad r_2 = 0$
where ϕ_{ref} means the reference angle of ϕ . The control system works as normal feedback control at $t \to \infty$.

(3) Transition mode $r_1 = \phi_{ref}, \quad r_2 = \phi$
The two DOF control system is designed so that θ should have no over shoot. Therefore, Part a and Part b collides softly.

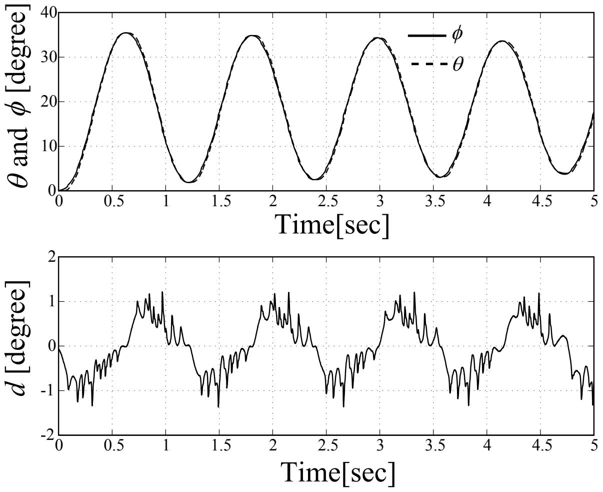

Figure 17: Experimental results of free motion

5.2 Preliminary Experiments of Free Motion

By using the control law of free mode, we made a preliminary experiment of free motion. Figure 17 shows the results. The upper figure shows the responses of θ and ϕ in a free swing of leg. The lower figure indicates the gap $d = \theta - \phi$. Since the opening of Part a and Part b is about ± 3[degree], and d stays within ± 1.3[degree] in Figure 17, free motion is realized.

Figure 18 illustrates the experimental results of switching control modes. The control modes are selected as follows.

(1) 0.0∼0.8[sec] : free mode

(2) 0.8∼1.6[sec] : transition mode

(3) 1.6∼5.6[sec] : drive mode

(4) 5.6∼6.6[sec] : drive mode

(5) 6.6[sec]∼ : free mode

In the graph of Figure 18, d exceeded ± 3[degree] which implies that the rubber material was compressed. In phase (2) the knee motor suddenly supported the gravitation. The knee joint was slowly driven by the motor and bending in phase (3). The foot was forced to push the floor in phase (4). Phase (5) shows the free swing motion. Free motion, drive motion, and smooth transition are successfully tested in the experiments.

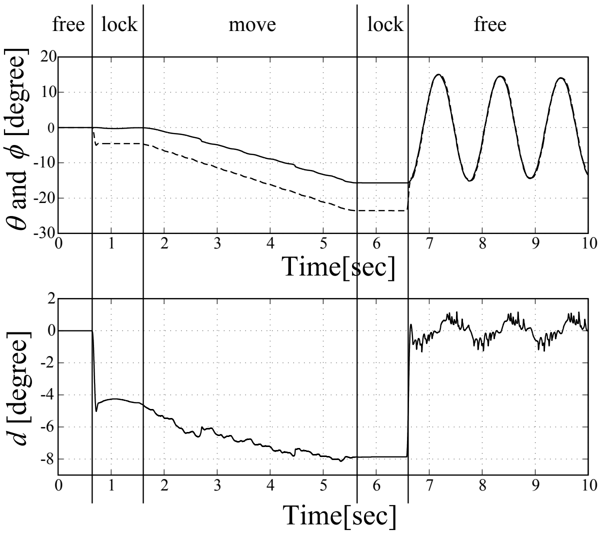

Figure 18: Experimental results of switching between the modes

6 Conclusions

In this paper, we discussed the mechanical design of humanoid robots. The driving mechanisms of joints are newly proposed in particular. The results of this paper are summarized as follows:

1. The double spherical joint was proposed as hip joints of humanoid robots. Replacing the conventional hip joints with the double spherical joint adds the mobility equivalent to the waist joints without actually adding them.
2. The backlash clutch was also proposed as a drive mechanism that can switch between drive and free modes. The backlash clutch can realize humanoid body compliant to the inertia and gravity force.
3. A humanoid robot was designed integrating both the double spherical hip joint and the knee joints with the backlash clutch.
4. The mode switching control of the backlash clutch was proposed based on the two DOF control system design. The performance of mode switching was preliminary confirmed by experiments.

Acknowledgments

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