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Abstract

A robot that simulates a human skier performing carved turns has been developed. Each leg had six degrees of freedom like those of human athletes. An on-board computer controlled the sequence of joint angles in an open-loop mode during skiing on an artificial grass slope.

The relations among joint motions, reacting forces and turn trajectory were investigated by programming various motions of the robot. At first, the effect of basic joint motions such as abduction-adduction and flexion-extension of the hip, knee and ankle joints were tried. Then the sequence of a top athlete's joint motions, measured in a separate study, was applied to investigate its effect on the ski turn. The human-inspired program produced a more even force balance between the skis and also a higher-quality turn.

The requirements for a successful physical model of a human skier are discussed.

Introduction

Athletes speak of the *effectiveness* of ski turns, an elusive quality but one related to low energy loss, a good body posture at each stage in the turn, and a cleanly carved snow track. They desire to know how to turn well, meaning what is the correct sequence of leg and body angles during the turn to produce the smoothest result. As a result there have been many studies to elucidate ski athletes' movements though various methods.

One way is the direct measurement of the motion of the skier in the actual turn on snow. Raschener et al (2000) measured joint angles and reacting forces in order to investigate the differences between carving turns and traditional parallel turns. Schiefermueller *et al* (2004)) investigated the movement of the centre of gravity in the various turning phases. Yoneyama *et al* (2000) measured the joint angles motion and acting forces to compare the turn motion using carving skis and that using traditional skis. Scott *et al* (2002) measured the joint motion angles in the measurement of top athlete's turn. These studies are valuable but tend to simplify the leg joint kinematics by ignoring or not measuring some of the degrees of freedom. Also it is quite difficult to know the true bone angles because the bones are so well padded with dynamically bulging muscle, fat and so on. Measuring all the skeletal degrees of freedom during real snow skiing is a challenging technical problem.

A second way to explore the relationship between the joint angles and ski turn quality is through dynamic simulation. The most common purpose of such modeling seems to be to support the investigation of the ski performance, for example Casolo *et al* (2000), Nordt *et al* (1999) and Kawai *et al* (2004). Because many assumptions are necessary in the simulation of the ski properties, snow properties and ski-snow contacting condition, there are few attempts to investigate the effect of skier's motion on the turn. Glitsch (2000) made a computer simulation of alpine skiing to investigate the effect of edging motion using a trapezoid mechanism model with rigid skis. Takahashi *et al* (2000) proposed that skiing may be understood from a simplified model with emphasis on the relationship between the centre of mass and the skis. Kagawa *et al* (2000) simulated the effective motion using a two dimensional analysis. Kawai *et al* (2004) developed a simulation system using a multi-body model fitted to a video image.

A third way to explore the relationship between joint angles and turn quality is to develop a physical model: a *ski robot*. Shimizu *et al* (1987) developed several manually controlled ski robots. The robots allowed exploration of the space of possible joint angle combinations and time sequence to produce effective ski turns. The robot work showed the important of thigh rotation, which causes a change to both the ski edge angle and pointing direction. Hasegawa *et al* (2006) simulated the turn on the robot which performs thigh rotation. Zehetmayer (2000) demonstrated several ski robots which could perform turns autonomously.

The purpose of ski robots is to allow experiments in which the actions of the skier (meaning the robot) can be controlled repeatably, or can be measured in ways that are not feasible with human athletes. The perfect robot skier would be like a human athlete in size, mass, mass distribution, power and degrees of freedom. Such a robot may arguably now be in reach of the best robot designers, but was beyond our capability. We will therefore try to explain why we built what we did, and to show that it may have some value as a model.

Why ski robot research?

1. The sequence of joint angles with time can be programmed, and the trajectory and acting forces can be recorded. The effect of a small change to the joint angle sequence can thus be brought out;
2. As a refinement of (1), a sequence of joint angles recorded from a human athlete can be applied to the robot. Each human athlete has a slightly different personal style and these can be examined in detail;
3. Conversely if a superior sequence of joint angles is developed for the robot, human athletes could be asked to try to imitate it. The robot could then function as a physical display or teaching system;
4. Since a robot can ski very consistently, meaning with the same joint angle sequence each time, it is a useful experimental platform for studying the properties of the skis.

Modeling considerations

A ski robot is meant to model a real skier as closely as possible, so we must examine in detail what types of correspondence are most important.

Force components during the turn

Fig. 1 shows a skier with gross forces. Analogous forces appear in both the robotic and human cases, even if the size or mass of the robot are very different from the human skier. We also note that since the gravity force and centrifugal force are both proportional to mass, the ratio of gravity to centrifugal forces depends only on the combination of slope angle, turning speed and turning radius. The reacting force from the slope surface is affected by the contacting angle between the ski and the slope surface, the mechanical properties of the slope surface and the friction coefficient between running surface and slope surface. Seen from this type of gross-forces perspective, the size, mass and mass distribution of the skier are not so important.

Mechanical properties of the ski

Although the turn radius of a ski depends on many parameters of the ski and contacting surface, in a pure carved turn the side-cut radius and elasticity of the ski are perhaps the most important parameters. In a ski robot experiment we have control over the slope angle and thus the velocities achieved. We can then – in principle at least - choose the side cut radius and stiffness for the robot skis so that the ratio of the gravity force to the centrifugal force is similar to the human case.

Mechanical properties of the slope surface

During skiing on real snow, the surface is compressed and becomes harder immediately under the ski, and this harder surface produces the reaction force. Real snow is a tremendously complex material which can be different from day to day on the same slope. Since our purpose was to examine slight changes in the joint angle sequences, we had to eliminate sources of variability and thus used an artificial slope surface. We must therefore examine whether an artificial surface can be a reasonable model for a real snow surface.

Since we intend to model only pure carved turns, the properties of the artificial surface in a "skidding" mode were not considered important. Instead there remains only the force of sliding friction acting along the carved path of the ski. This force is mainly from the sliding friction of the ski but can also include a component of the snow-normal forces in the velocity direction because of the elastic bent shape of the ski. The coefficient of sliding friction becomes the main measure of equivalence between the snow surface and artificial surface for our purposes, although the peak force that can be generated in the radial direction before slipping places an experimental limit on the centrifugal acceleration.

The robot experiment system

Ski robot

Fig. 2 shows a schematic view of the robot, with dimensions shown in Fig.3. The length of the leg and the width between the hip joints were 300mm and 160mm respectively. The ratio of the hip joint width to the leg length was about 2, whereas human beings typically have a ratio of about 3. The mass of the upper body was 1.3kg and of the lower body 2.3kg, for a total mass of 3.6kg. The overall size and leg part lengths were chosen to be human-like in proportion within the constraints of the sizes of the joint servomotors. The centre of mass was 224mm above the ski running surfaces. This means that the ratio of the height of the mass centre to the width between the two skis was about 1.5, whereas in a human athlete it is typically 2.5 to 3. The centre of mass of our robot was thus relatively lower than for a human being. We tried a version of the robot with the "human" ratio but found it very difficult to control on the slope because the most common behaviour was to fall over. The lower ratio of mass centre height to ski width of our robot was thus a design compromise and limitation of this work. The non-human ratio affects the kinematics of the legs and centre of mass. For example if the robot performs a turn using hip joint abduction-adduction, the centre of mass of the robot will approach the slope more than for a human athlete, for the same leg angle. Similarly if the robot "squats" using a combination of flexion of the knee and hip, the centre of mass will fall more than for a human, for the same flexion angle.

Each servomotor had a maximum torque of about 2Nm, whereas in a human athlete the hip joint and knee joint may produce more than 100Nm. The working torque in the robot was thus only about 2% of that in human athletes. However the mass of the robot was about 5% of a typical human. The ratio of working torque to weight force was thus smaller for the robot, relatively speaking. Our ski robot was not able to jump by hip and knee joint motions, as all ski athletes are well able to do, and thus could only ski in a fairly passive mode more like a recreational skier than an athlete in competition.

Skis used in the robot experiments

It is typical for a human athlete to choose skis about as long as their height. Applying this rule to our robot, we chose ski length 500mm. The boot centre was situated at 45% of the length from the tail. The side-cut radius of the ski in the robot experiment was 3m according to the expected turn radius. The centre of the side curve was also at 45% of the length from the tail. The skis were made of 8mm polycarbonate. The thickness was chosen so that with 10N applied to the boot centre, and an edge angle of 15°, the whole inside edge of the ski was in contact with the slope surface. Experiments showed that a thinner ski led to skidding in the later part of the turn cycle, but a thicker ski would touch the slope only at the top and tail points. Skis for human athletes have a gradient of stiffness along the length, whereas our robot skis were very plain.

PTFE tape was applied to the ski running surface to reduce friction.

Test slope

The test slope was 11m long, 3m wide and had an inclination of 20°. The slope was covered with a carpet of plastic artificial grass.

The coefficient of friction between the test slope and the PTFE-coated skis was 0.24 for straight skiing and 0.26 for edging, whereas the coefficient of sliding friction for a ski on snow is about 0.1. If the ski robot were placed on the artificial grass with slope 15°, the downhill sliding speed would remain about constant during the descent. To allow the robot to pick up speed before turning, the test slope angle was made 20°.

When the edged ski was pressed against the slope surface during the turns, the ski edge went into the artificial grass between the “stems”. The ski edge was thus supported by the elastically deformed grass and by the woven surface under the grass stems. This type of support was less effective than that of real snow and radial sliding occurred quite readily. The artificial grass slope was thus a surface with higher tangential friction and lower radial support than real snow, a limitation of this work.

Instrumentation

The experimental plan was to measure the trajectory of the robot using a video camera, and to measure front and rear ski-normal “boot” forces.

The load cell arrangement may be seen in Fig. 5(a). The custom-made load cells were based on a parallel-plate structure and strain gauges, and were sensitive mainly to forces normal to the ski. The rear connection between the load cell and ski had a sliding joint to permit the dimensional change associated with ski bending.

A distance and speed-measuring device was mounted at the rear of each ski as shown in Fig. 5(b). These consisted of a pair of light plastic toothed wheels on a common shaft. An optical encoder in the assembly measured the rotation of the wheels, which turned with low friction. This sensor was used to help compute the ski trajectory and also to detect the start instant in each experiment, when the robot velocity had reached a programmed threshold.

A video camera placed at the bottom of the slope captured each skiing event. To assist the analysis of the video frames, an electric lamp was set at the front and rear end of each ski. These were turned on under software control at the start instant during the ski motion.

Operating system

The control system is illustrated in Fig. 6. A computer and batteries were installed in the upper body. The computer was an "Eyebot" developed by Prof. Braunl of The University of Western Australia. The Eyebot controlled the servomotor angles. An AVR coprocessor was used for data collection from the load cells and wheel encoders, and was connected by a parallel cable to the Eyebot. It was possible to capture a time history of force and position change in the memory of the Eyebot. The batteries were of the lithium-ion type and there was a separate battery for logic and for servomotors

Motion program

The motion programs were open-loop histories in which each joint angle was programmed as a sine function with a certain amplitude and phase shift. A typical experiment trajectory and robot posture are shown in Fig. 7. The program parameters were chosen so that the robot made at least two turns after an initial straight descent. When the robot reached 1 m/s in the descent, it always turned to the left at first, then to the right and finally to the left again. The first left turn was thus a half-turn but one full cycle followed. Owing to the limit of the slope length, the main region of interest was the first turn change from the left turn to the right turn and the following first half and second half of the right turn. In each motion program it was found that the range of parameters for a successful turn was quite narrow. A slight change in the amplitude or phase would mean either stable turn behaviour or the more usual falling and crashing behaviour.

Experiments

As a basic examination of the effect of joint motion, simple motion programs were created to activate only the abduction-adduction motion and only the flexion-extension motion.

Effect of abduction-adduction

Fig. 8 shows results from an experiment with abduction-adduction motion only. The joint angle history, resultant forces on both skis and sliding velocities are shown in the left side. The fluctuation in the forces may be due to vibration of the robot body. The turn trajectory inferred from the video footage is shown in the middle. The differences in the apparent ski lengths and some anomalies in the ski directions may be caused by errors in the ski lamp positions identified in the video frames. If we compare the joint angle change diagram and the turn trajectory trace, it will be seen that the time of the turn direction change coincided with the time that the joint angle crossed zero. This means that the ski direction change was determined mainly by the edge angle.

Comparing the force on the left and right foot with the joint angle history and turn trajectory, it is noticed that at first, when abduction to the right started, the right load increased. Then, when abduction was reduced, the left load increased. In the next half right turn, the right load was larger than the left load. This means that during the first half turn, the inside load was larger than the outside load. This may be due to the low skiing velocity, which meant that the centrifugal forces were small and the robot was essentially in a static posture on the slope. This caused an increase in the force on the foot which was situated on the down-slope side. In the second half of the turn, both loads were nearly equal. From our other work with the measurement of human skiers (Scott 2002), we know that a human skier adopting an abduction-adduction pose will tend to have a higher force on the outside leg in nearly every case, even in the first part of a turn.

Effect of flexion-extension of the knee joint

A motion program was made such that the ski was controlled by a combination of flexion of the hip, knee and ankle joints as shown in Fig. 9. The inside ski was effectively lifted but remained parallel to the outside ski. The robot's body was thus inclined towards the inside of the curve as expected. It may be considered that the change of the ankle joint angle is small in the case of human ski athlete because the foot is fixed in the boot. But it is necessary to keep the inside ski parallel to the outside ski without moving much forward of the outside ski. The edge angle can be found from a simple geometric consideration of the separation of the skis and the amount of lift. The measured forces, velocity, turn trajectory and robot posture are shown in Fig. 10. The turn change occurred at the same time as the change from flexion to extension. The inside foot force was again larger than the outside foot force during the first half of each turn. The skiing velocity increased gradually during the experiment. These results were similar to those for the previous experiment (abduction-adduction only). The turn trajectory was also similar although in this latter experiment there was more radial skidding. The successful range of the motion angles for this flexion-extension experiment was found to be narrow. This indicates that given our choices of velocity, slope angle, side-cut radius and ski stiffness, the space of the possible edging angles was limited by the dimensions and mass of the skiing robot.

From these experiments, we found that both abduction-adduction and the ski-lifting approach were useful motions for effective ski control and turning. In both motions, the robot centre of mass crossed over the skis perpendicular to the skiing direction during the turn change.

Emulation of the motion of a top athlete

Measurements of a top athlete, Mr Hirasawa, a former world cup racer, revealed that he turned his waist to face inside the turn arc (Scott *et al* 2004). A motion plan for the robot to simulate this situation was programmed as shown in Fig. 11. The main motion was flexion-extension with a small amount of abduction-adduction. Thigh rotation and lower leg rotation were added to face the waist inside the trajectory tangent as shown in the top view on the upper right side of the figure. This combination of motions moved the centre of mass slightly forward and made the waist turn inwards. The resulting trajectory is shown in the lower part of Fig. 12. If the force traces are compared with those from the previous experiment (no thigh or lower leg rotation), the force was more evenly shared between the feet. The turn also became more stable and the change of the skiing direction in the first half of each turn was faster. We think this may be due to the motion of the centre of the mass of the robot. The ski posture with the waist facing inward may be a valuable approach for athletes who wish to have a smaller radius in the first half of each turn.

Discussion

Comparison with human skiing

When a human athlete makes a long turn, the load on the outside ski is usually about double that on the inside ski during the whole turn cycle, including the first half (Scott *et al*, 2004). That work also showed that both the inside and outside leg forces reduce to nearly zero at the turn change. Human skiing is thus very much governed by dynamic forces. However, in our robot experiments, the skiing velocity in the right turn increased from 2 to 3 m/s with a turn radius of about 7m. The centripetal acceleration was only about 0.6 to 1.3m/s^2. However in an example of top athlete's long turn the speed is about 16m/s and the radius perhaps 30m. The centripetal acceleration in the human case is thus about 8m/s^2, similar in magnitude to gravity. Compared to the robot, the posture of the human athlete is much more steeply inclined towards the centre of curvature. In order to achieve the same centripetal acceleration in the robot experiment as in the human one, the turn radius must be reduced or the velocity must be increased. But when such approaches were tried in the experiment, skidding of the ski has been observed. As observed above, (1) our artificial running surface was unfortunately rather different from snow for the case of radial (outward) forces, and (2) the robot has a much lower power-to-weight ratio than a human being.

Significance of the robot experiment

The robot is still in development and much remains to be done. However, we think it is still able to tell us something about the real effect of each of the joint motions and other factors of the ski turn, at least in a qualitative sense.

The robot has allowed us to separate the effect of each of the joint motions. Abduction-adduction and flexion-extension motions have been found to be effective because they directly change the edge angle of the ski. By emulating the detailed joint angles of a skilled athlete, we were able to further improve the skiing performance of the robot. A series of leg angle changes to point the waist inward during the turn, modelled on the human expert, was found to be particularly effective. Load sharing between the skis was improved and the downhill force increased in the first half of each turn. We expect to extend this approach in future by applying observations from the measurement of more athletes.

Conclusions

Some steps to develop a robot experiment system to investigate the effect of joint motions on the ski turn have been achieved. Requirements for physical modeling using a ski robot have been investigated. A robot that had degrees of freedom in the legs like those of a human skier was developed to investigate the relations among joint motions, acting forces and turn trajectory. The robot had force sensors between each ‘foot’ and ski, and an odometer at the rear of each ski. The trajectory was measured by a video camera mounted at the base of the slope. The servomotors in the robot were driven in an open-loop mode according to a chosen pattern of sinusoidal angles. From experiments we found that skiing could be achieved provided the joint angle history was carefully tuned to prevent falling over. Also:

1. A simple sinusoidal angle change in the abduction-adduction motion and also in the flexion-extension motion could be tuned to produce an effective turn change followed by a carved turn arc.
2. A motion program developed from measured ski athlete data, and having flexion-extension, abduction-adduction combined with thigh rotation and lower leg rotation produced better foot force balance and a steady smooth turn.

The ski robot was quite different from a human being, limiting its usefulness as a model. The main issues were the non-human ratio of mass centre height to ski separation distance, the ratio of the power of the motors to the mass, and the frictional properties of the non-snow slope surface.

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Fig. 1 Force components parallel to the snow surface during a ski turn

Fig. 2 Schematic view of the ski robot

Fig. 3 Dimensions of the ski robot

Fig. 4 Joint motions of the ski robot

Fig. 5 Load cells, a speed meter installed on the robot

Fig. 6 Operation system of the ski robot

Fig. 7 Expected turn trajectory on the slope

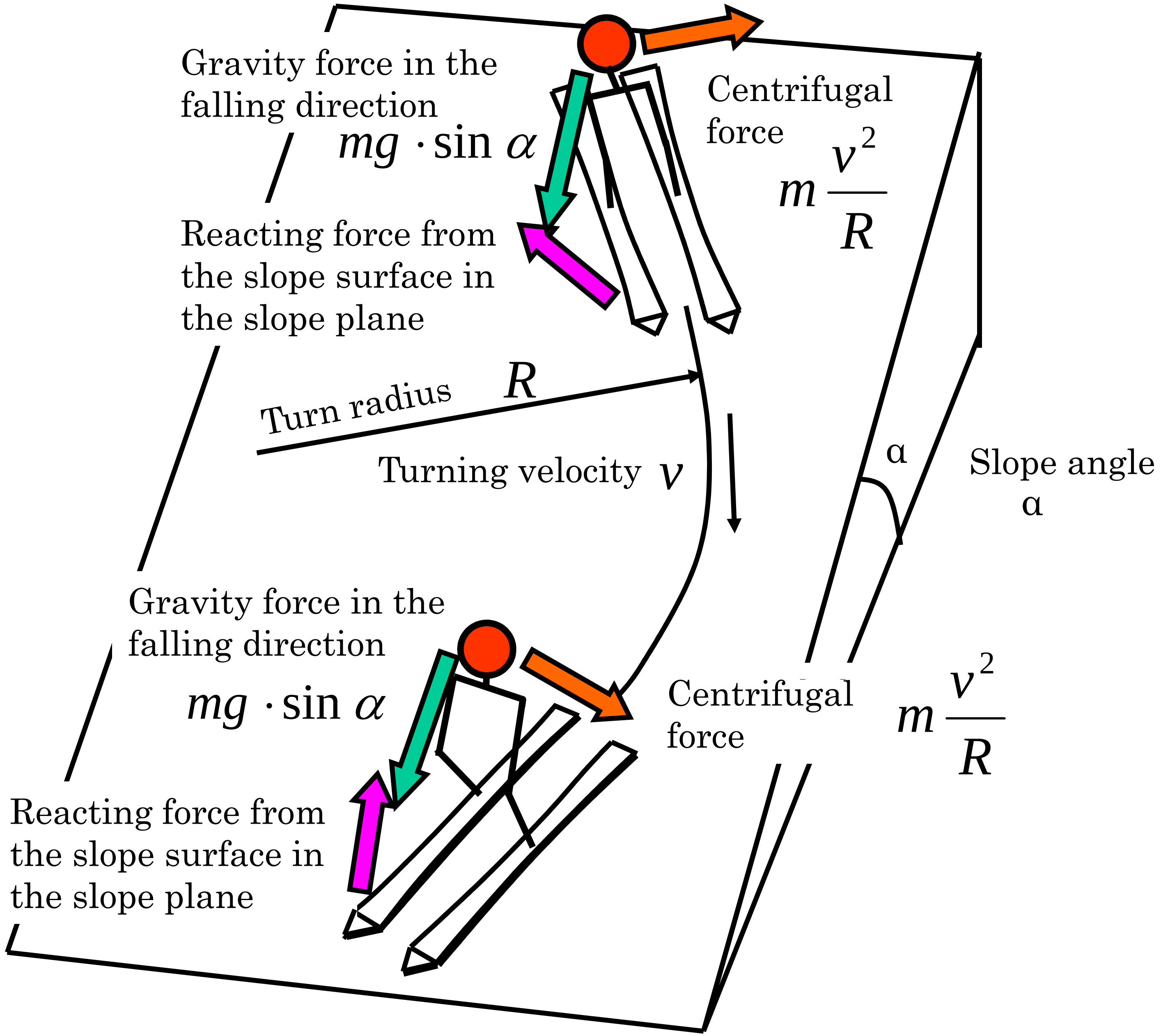
Fig. 8 Typical ski robot turn by abduction-adduction

Fig. 9 Joint angle diagrams for flexion-extension motion

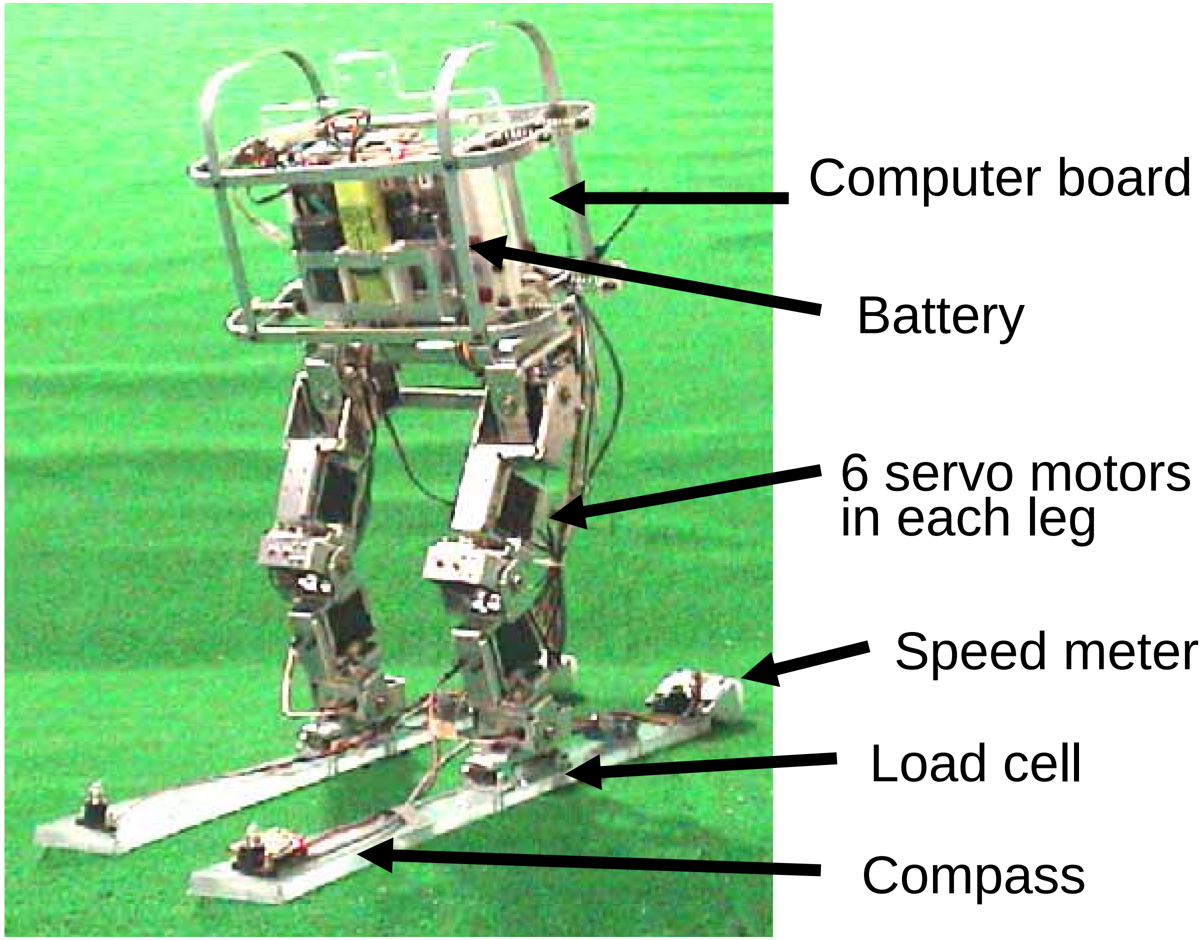
Fig. 10 Typical ski robot turn by flexion-extension motion

Fig. 11 Joint motion diagrams inspired by a top athlete’s motion

Fig. 12 Typical ski robot turn using the program inspired by a top athlete’s motion



Gravity force in the falling direction
$mg \cdot \sin\alpha$
Centrifugal force
$m\frac{v^2}{R}$
Reacting force from the slope surface in the slope plane
Turn radius R
Turning velocity v
α
Slope angle α
Gravity force in the falling direction
$mg \cdot \sin\alpha$
Centrifugal force
$m\frac{v^2}{R}$
Reacting force from the slope surface in the slope plane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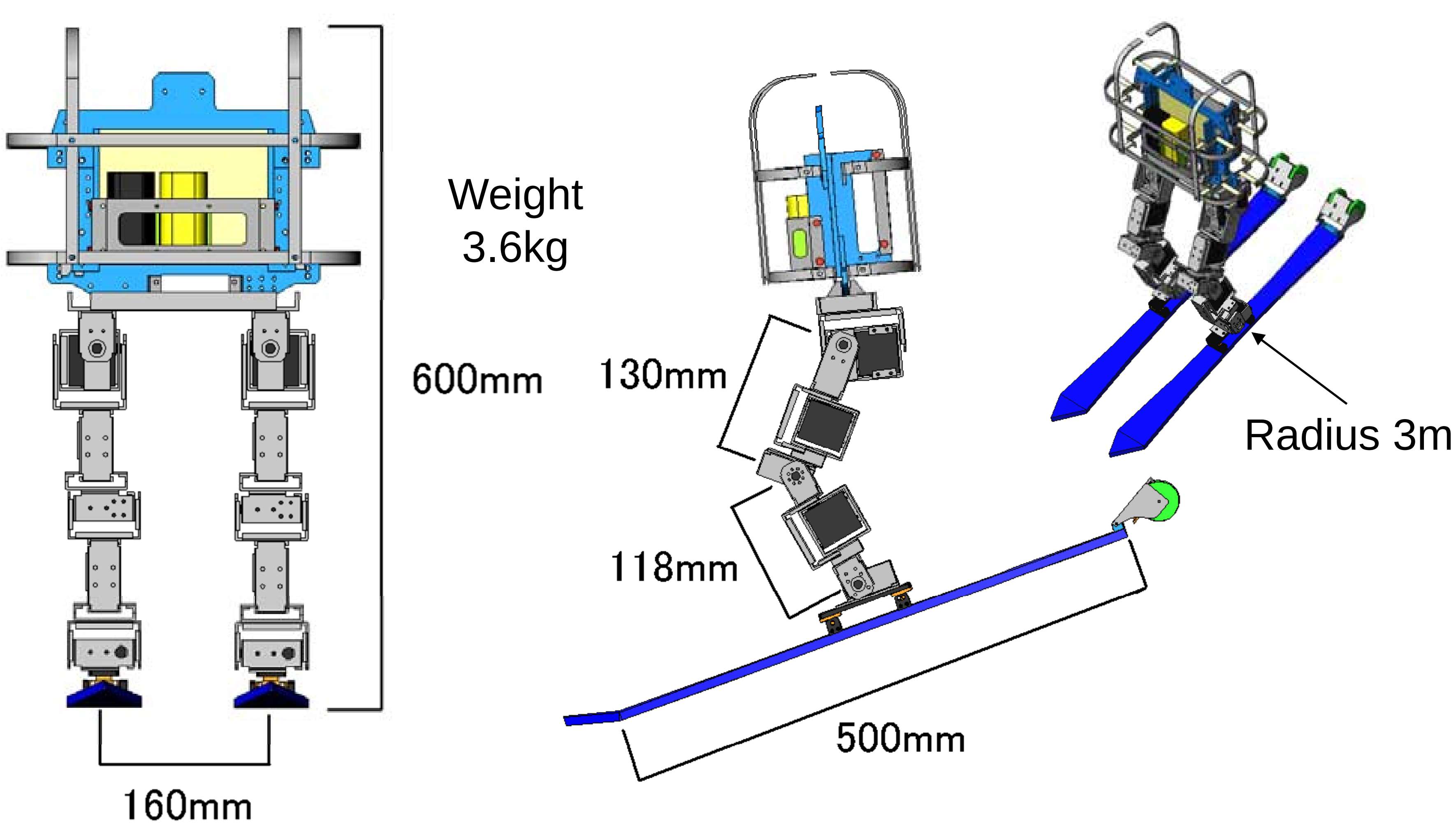
6 servo motors
in each leg
Speed meter
Load cell
Compass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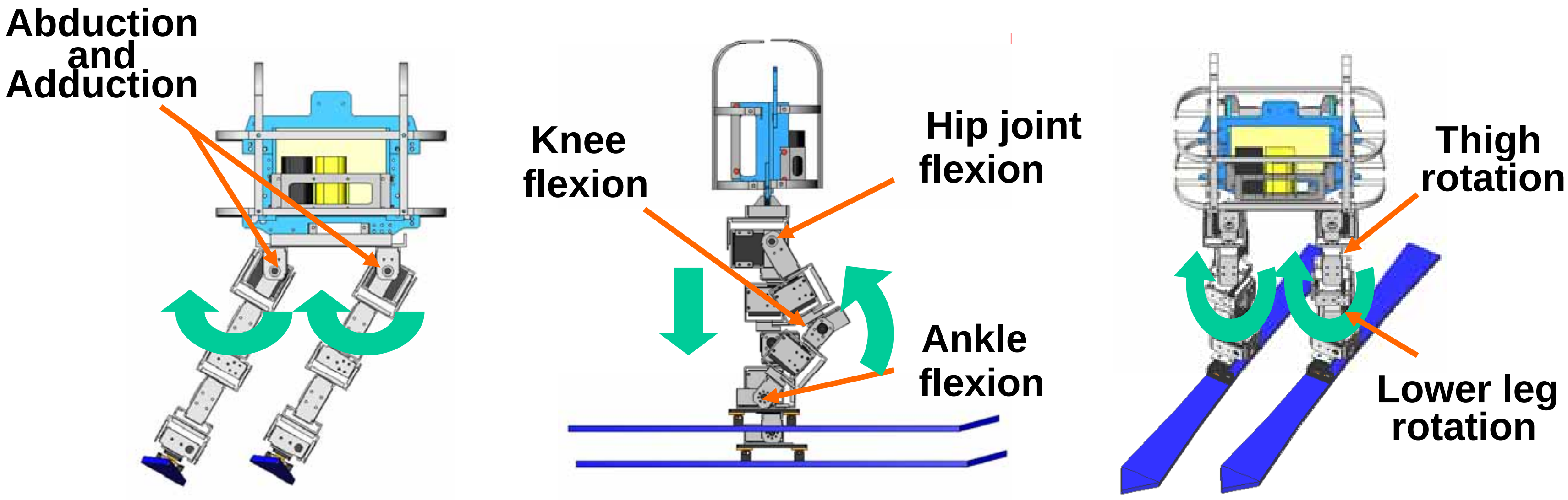
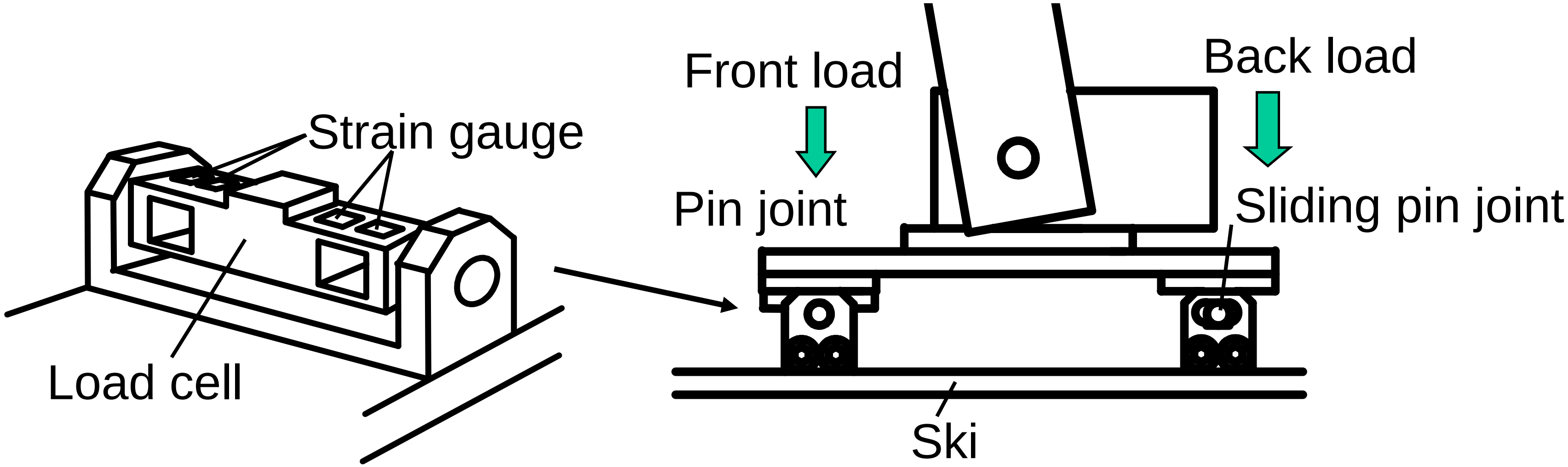
500mm
Radius 3m



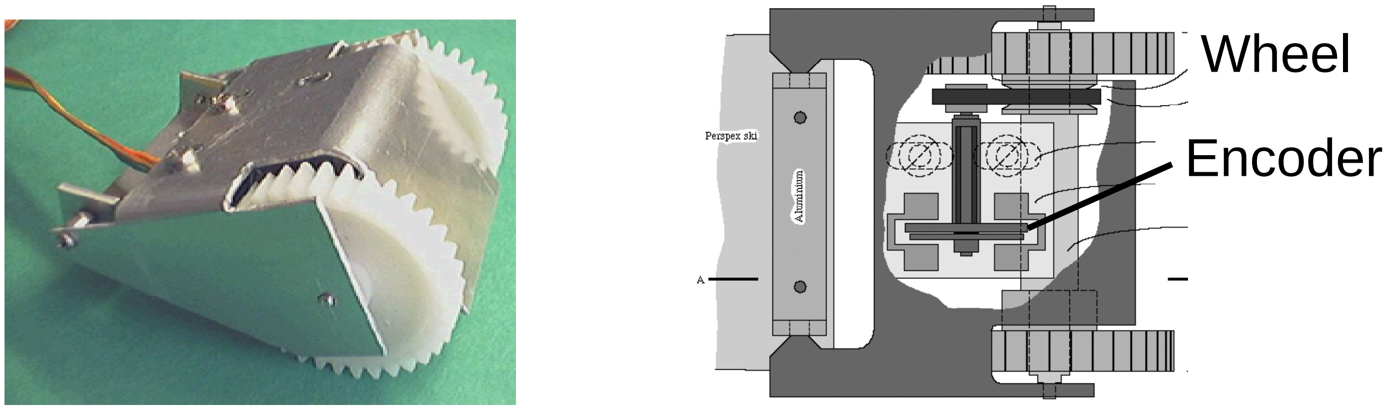
(a) Abduction and adduction

(b) Flexion-extension

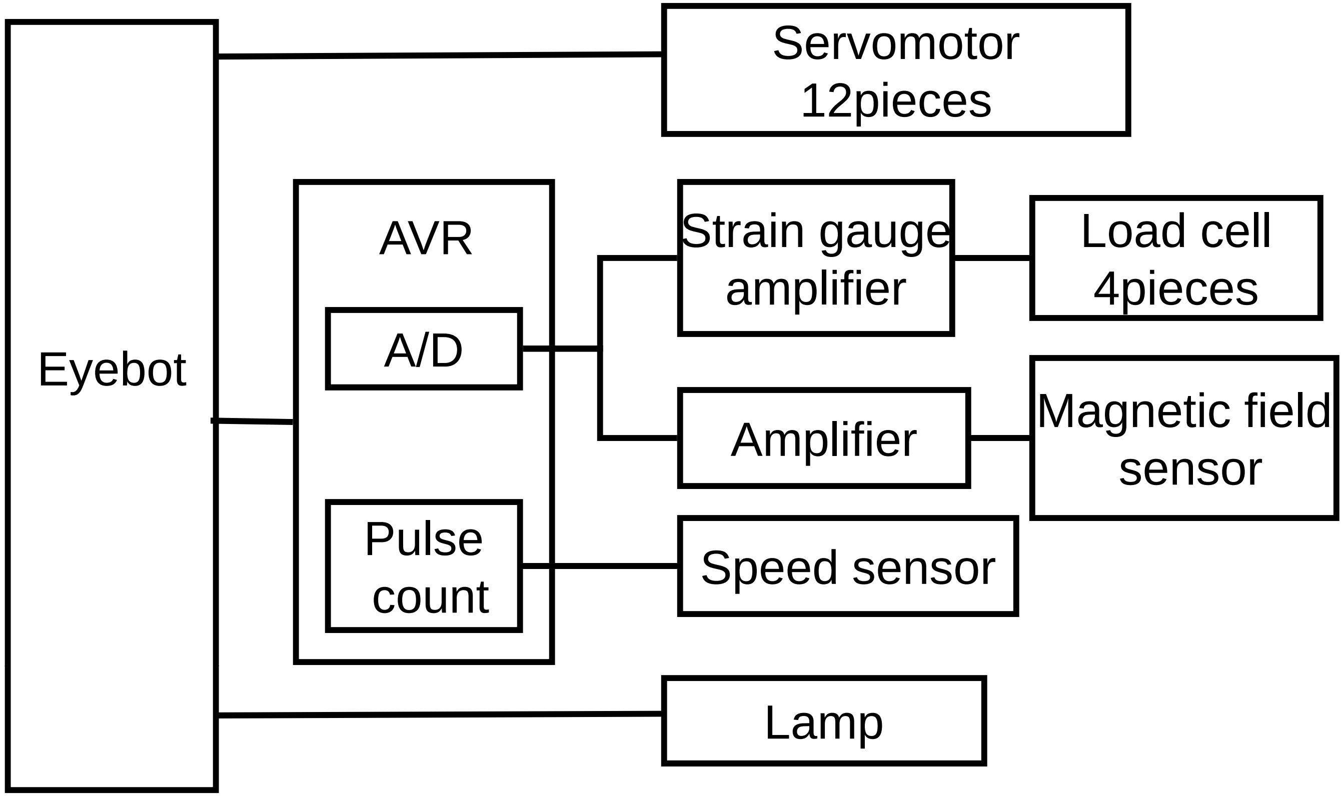
(c) Thigh rotation, lower leg rotation



(a) Load cell



(b) Speed meter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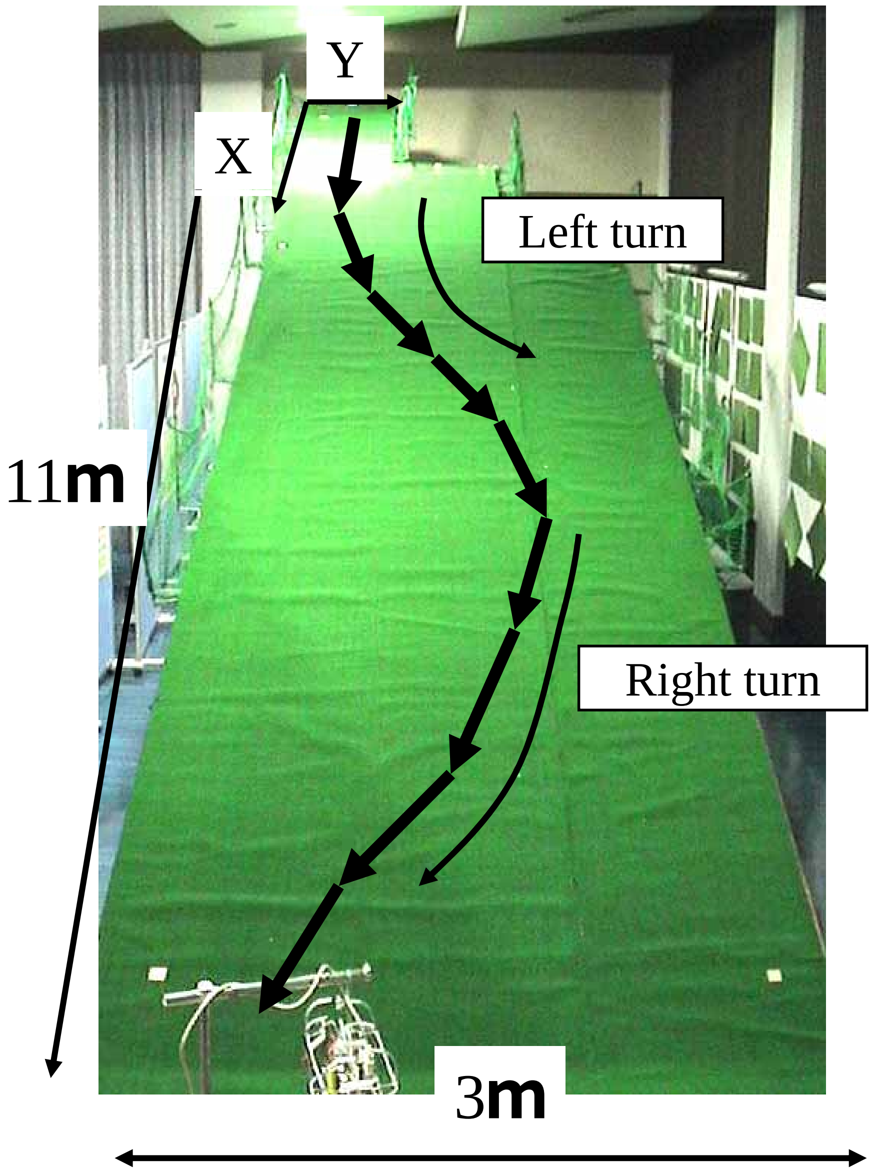
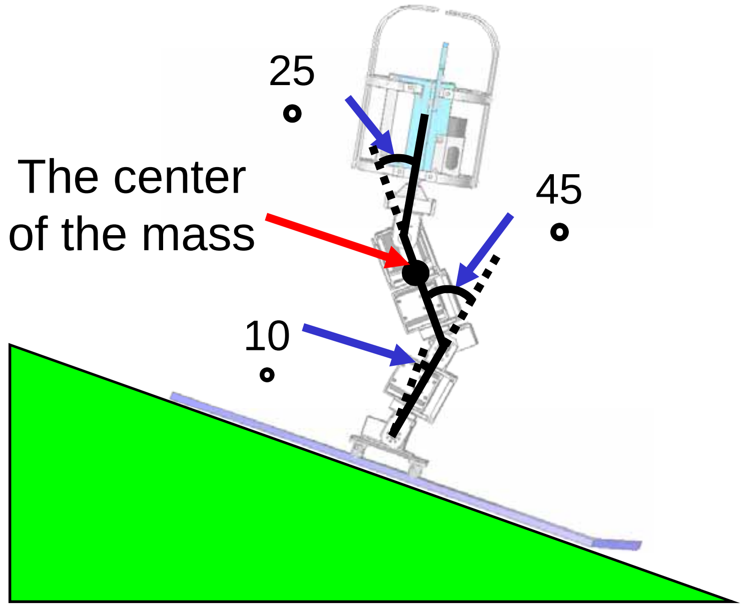
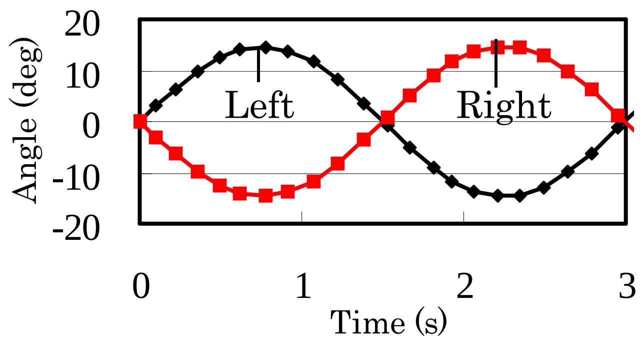
AVR
A/D
Pulse count
Strain gauge amplifier
Load cell 4pieces
Amplifier
Magnetic field sensor
Speed sensor
Lamp

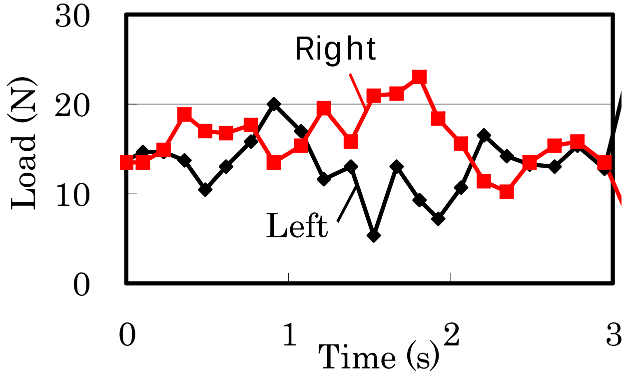




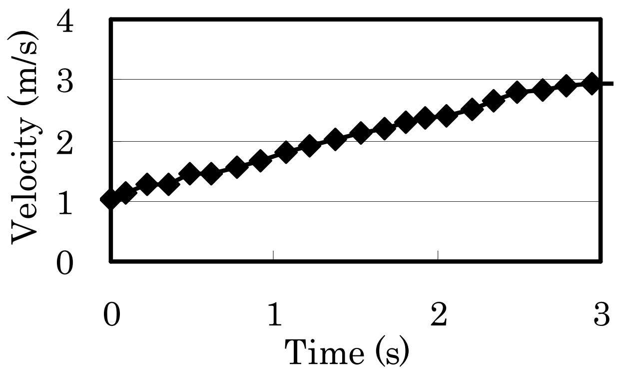
Initial posture of the robot



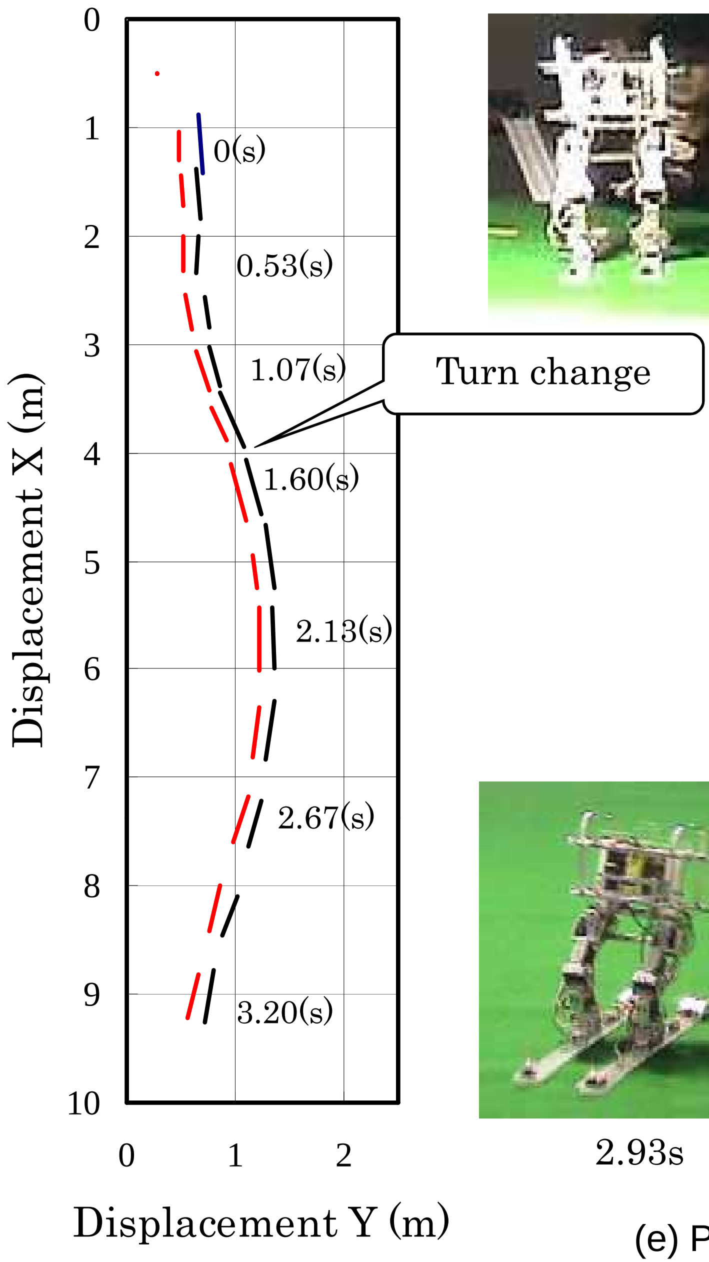
(a) Abduction-adduction diagram



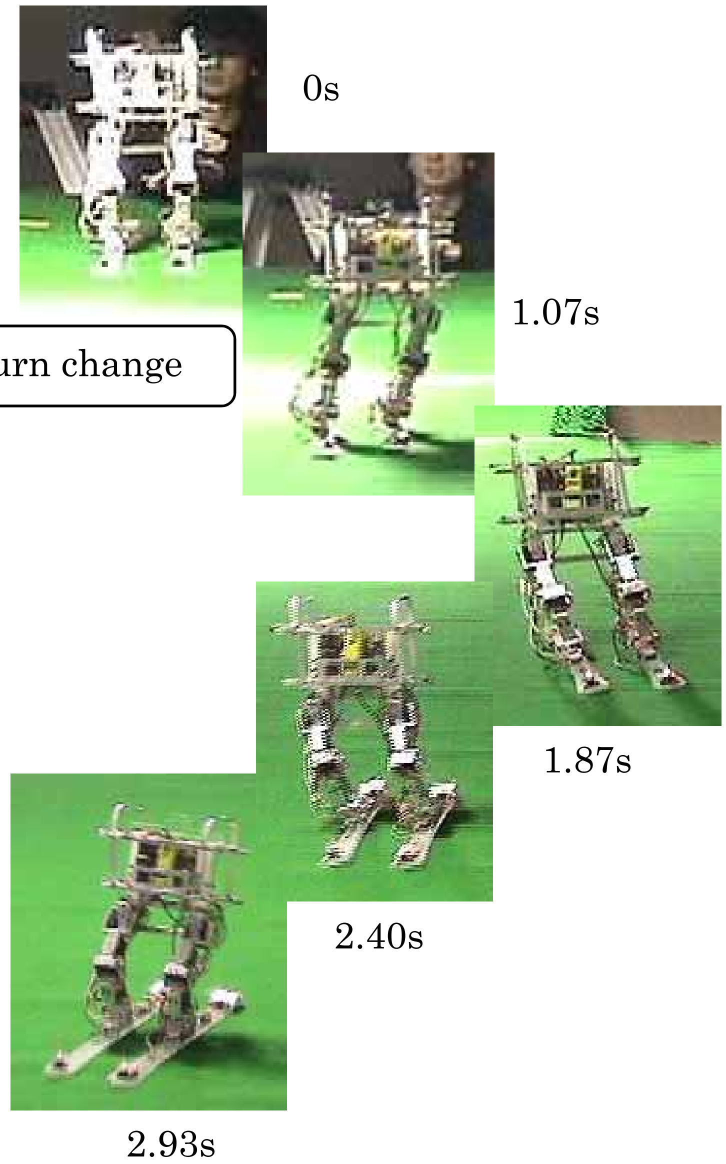
(b) Applied force on the ski



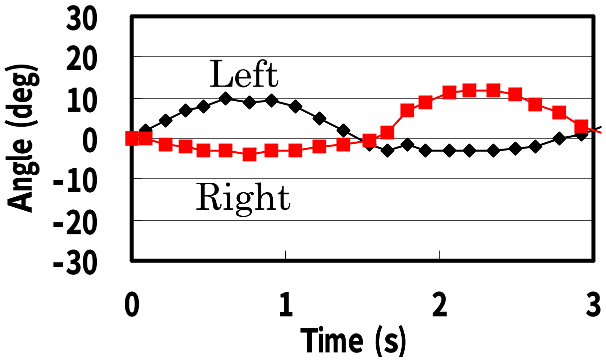
(c) Velocity



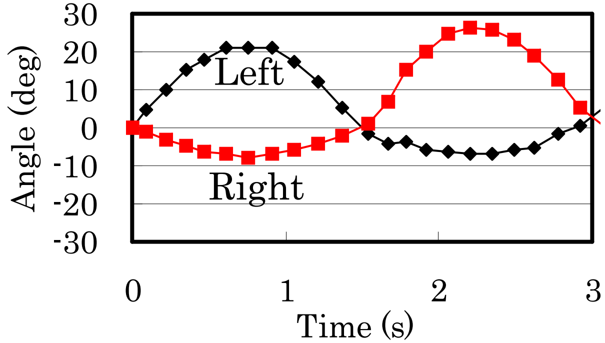
(d) Turn trajectory



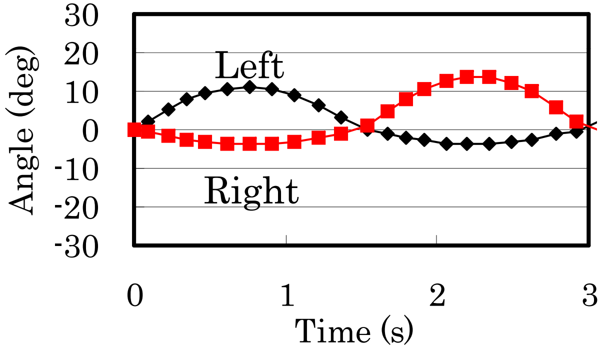
(e) Postures of the robot during the turn



Hip joint flexion

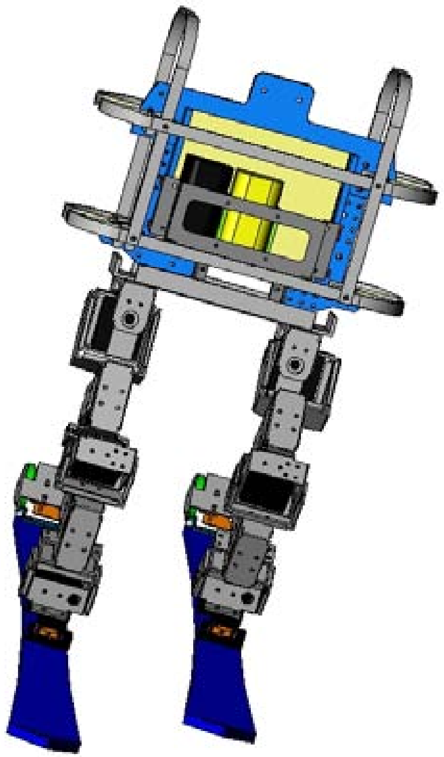


Knee flexion

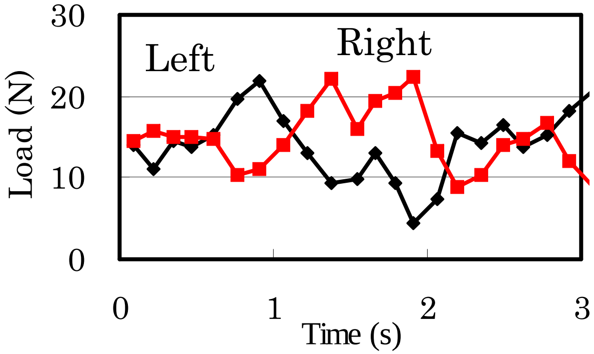


Ankle flexion

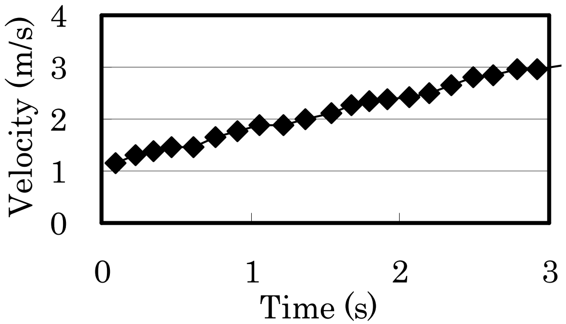
(a) Flexion-extension diagram



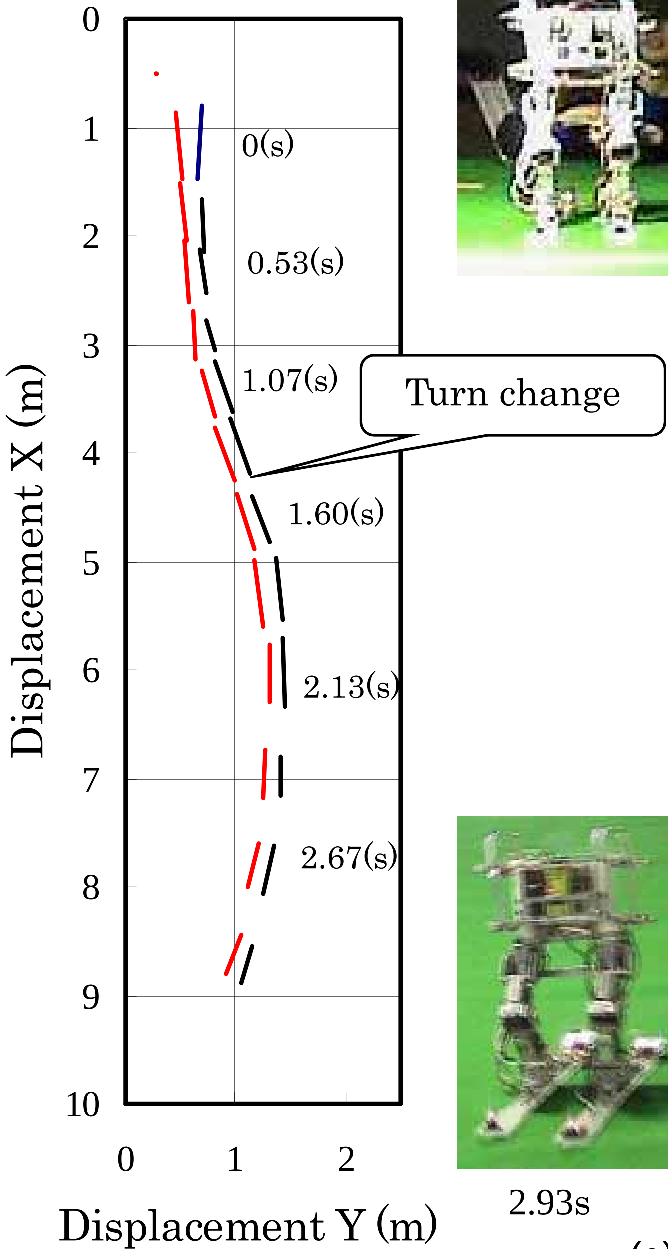
Posture at the
maximum left flexion



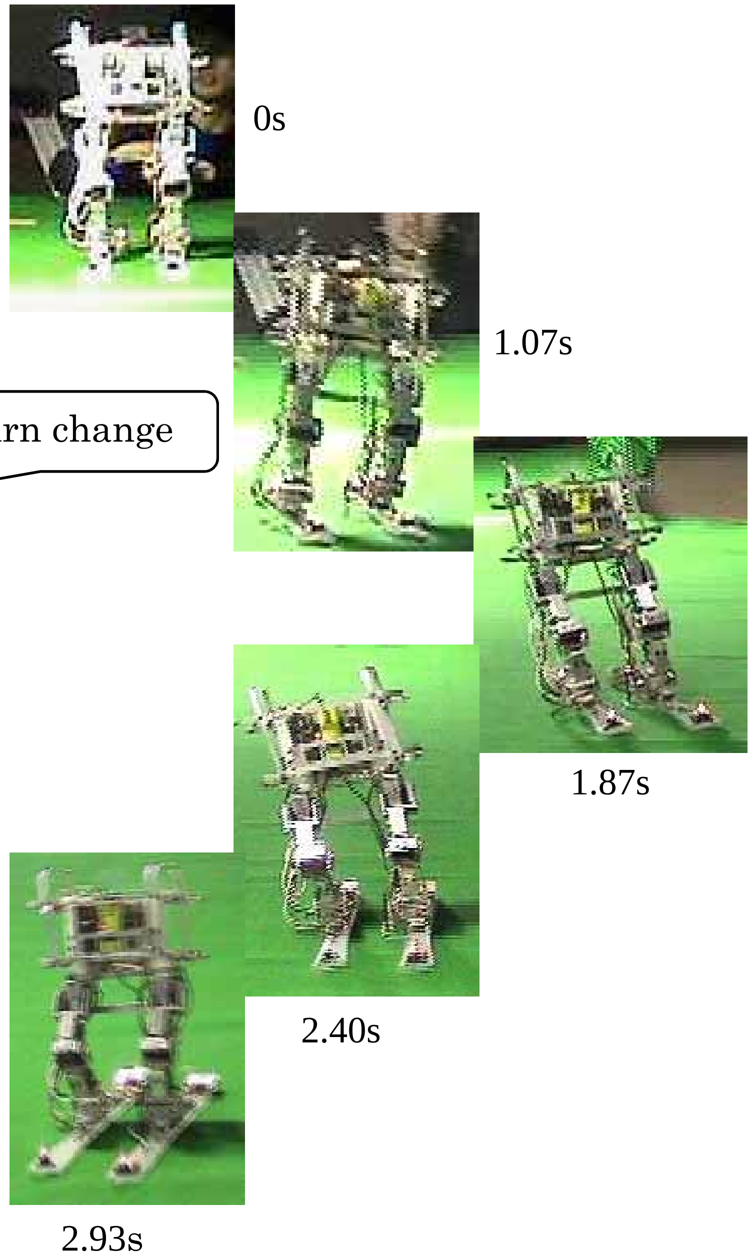
(b) Applied force on the ski



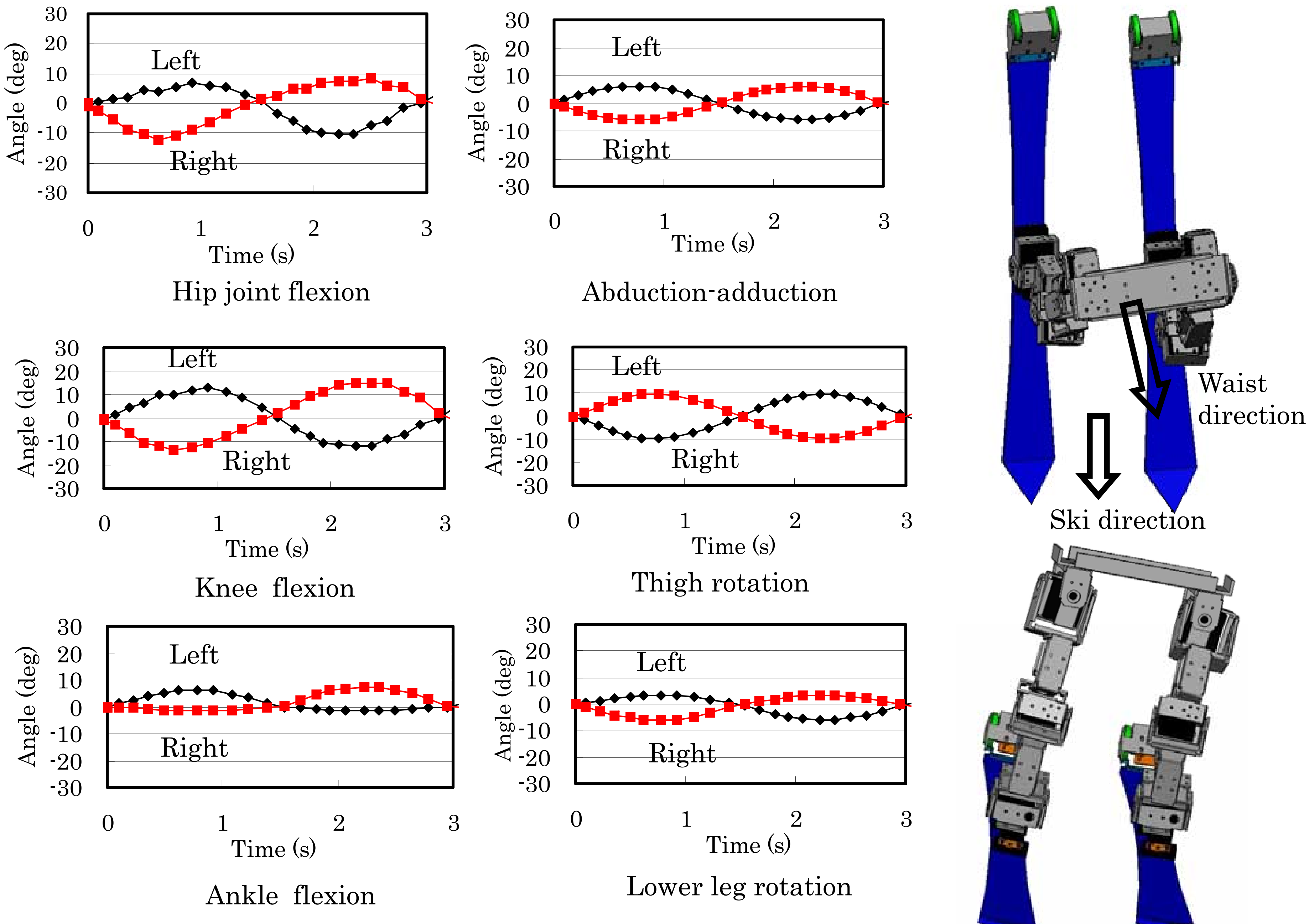
(c) Velocity



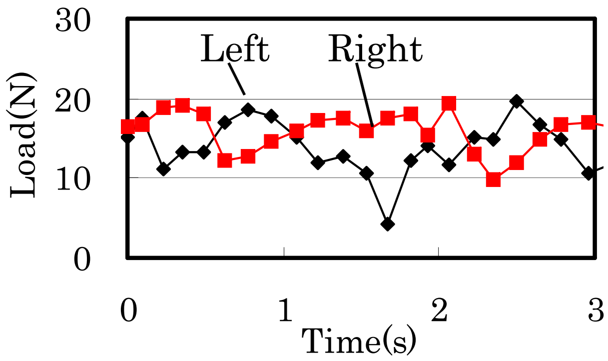
(d) Turn trajectory



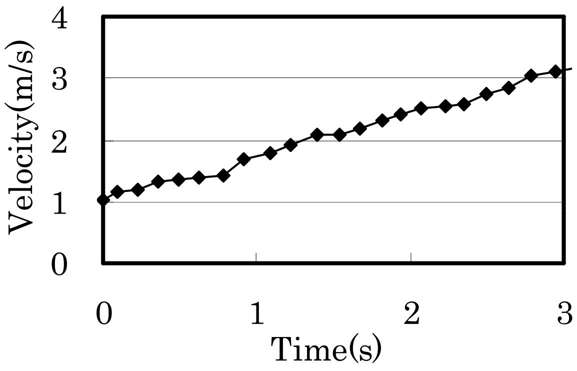
(e) Postures of the robot during the turn



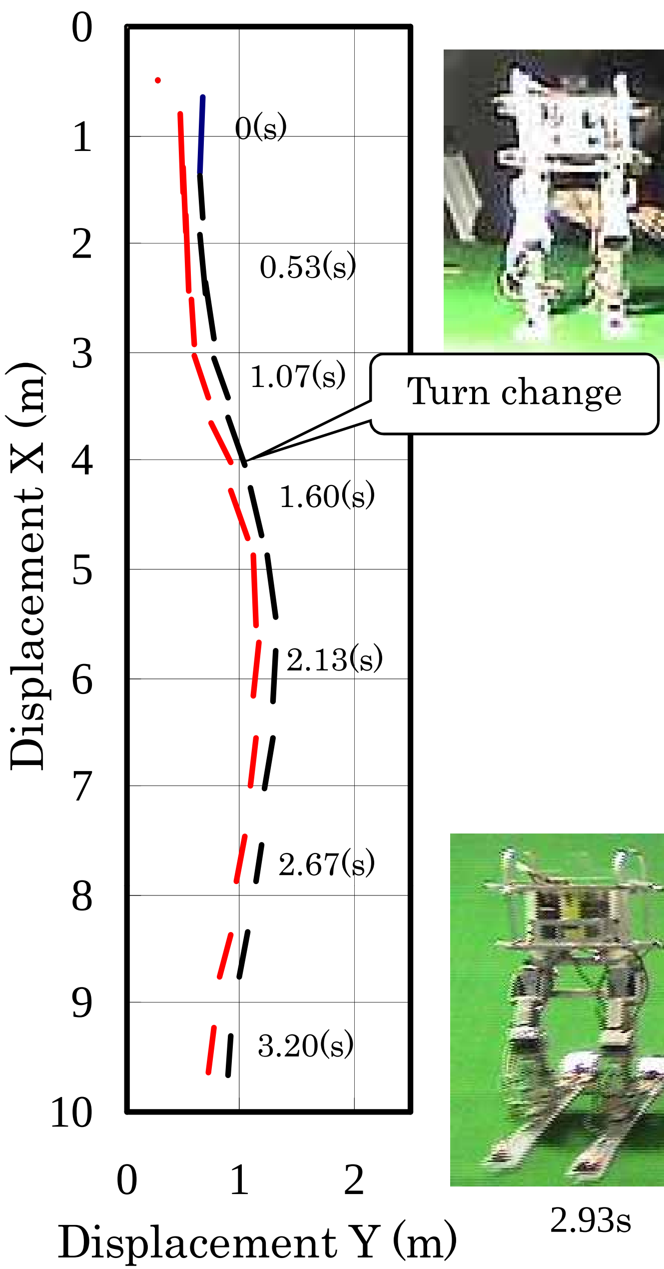
(a) Motion diagram



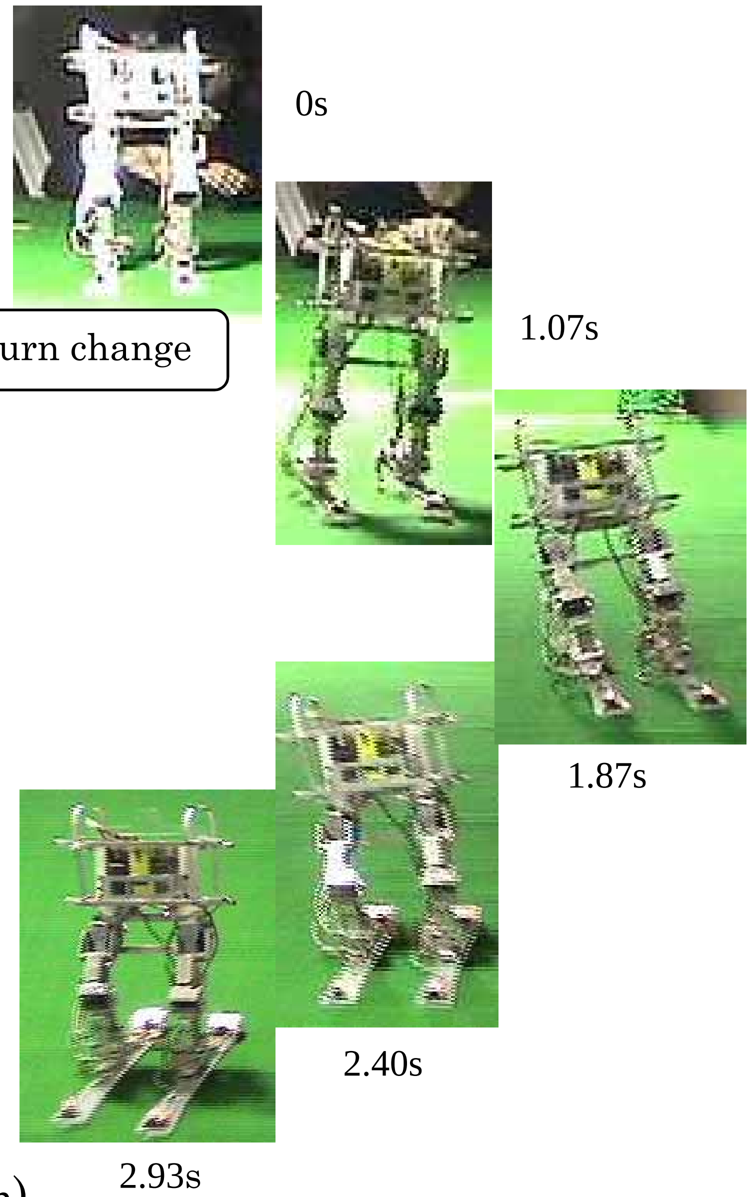
(b) Applied force on the ski



(c) Velocity



(d) Turn trajectory



(e) Postures of the robot during the turn