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Comparative Evaluation of Locomotion Modes in Virtual Environments

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ABSTRACT

This paper describes about experiments of navigation performance using three locomotion metaphor:walking, riding,and flying. We have developed a new locomotion interface for walking about virtual space. Torus-shaped surfaces is selected to realize the locomotion interface. The device employs twelve sets of treadmills. These treadmills are connected side by side and driven to perpendicular direction. Infinite surface is generated by the motion of the treadmills. The walker can go to any direction while his/her position is fixed in the real world. The device is named "Torus Treadmill." We introduced a motion base for riding through virtual space. Navigation performance is measured by path reproduction tests. Subjects were immersed in a virtual grass-covered plain on which two cone-shaped target objects are placed. At first the subjects traveled to the target objects. After they finished it, the target objects disappear and the subjects were asked to go to the place where the target objects were placed. We compared three locomotion modes: walking on the Torus Treadmill,riding on a motion base, and moving by pure joystick operation. The results of the experiment showed that accuracy of path reproduction of Torus Treadmill mode is better than that of motion base mode, and that of motionbase mode is better than Joystick mode.

Keyword: locomotion, walking, riding, navigation, path reproduction.

1. Introduction

In most applications of virtual environments such as training or visual simulations, users need good sensation of locomotion. There are three typical locomotion metaphor: walking, riding, and flying. Flying through virtual space has been often realised by pure joystic operation or gesture input. This is the most popular method for traveling about virtual space. However, pure joystic operation doesn't provides the user to proprioceptive and vestibular sensation.

Riding through virtual space is also a popular method for locomotion. Riding on a motion base has been often used in driving simulator or flight simulator. A motion base generates vestibular sensation for acceleration. It has often been suggested that the best locomotion mechanism for virtual worlds would be walking(Darken et al.,1998). It is well known that sense of distance or orientation while walking is much better than that while riding on a vehicle. However, proprioceptive feedback of walking is not realized in most applications of virtual environments. This paper introduces a new locomotion device which provides sense of walking. We have developed several prototypes of interface device for walking since 1989(Iwata et, al. (1990, 1992, 1996)). From the results of the research, we found that infinite surface is an ideal device for creation of sense of walking.

We selected a torus-shaped surface to realize the locomotion interface. The surface is implemented by twelve sets of treadmills. These treadmills are connected side by side and driven to perpendicular direction. Infinite surface is generated by these treadmills. We call the device "Torus Treadmill." The motion of the feet is measured by magnetic sensors. The floor moves to opposite direction of the walker corresponding with the result of measurement, so that motion of the step is canceled. Position of the walker is fixed in the real world by this computer controlled motion of the floor. The walker can freely change the direction of walking. An image of the virtual space is displayed in the head-mounted display(HMD) corresponding with the motion of the walker. Navigation performance is quantitatively measured using three locomotion modes. In order to remove bias caused by method of evaluation, we selected path reproduction tasks. Subjects were immersed in a virtual grass-covered plain on which cone-shaped target objects are placed. At first the subjects traveled to the target objects. After they finished it, the target objects disappear and the subjects are asked to go to the place where the target objects were placed. We compared three locomotion modes: walking on the Torus Treadmill, riding on a motion base, and moving by pure joystick operation. If optic flow alone is sufficient to allow a user to reproduce the path, subjects should perform equally well in these three locomotion modes. Of secondary interest is whether the Torus Treadmill can provide natural walking for first-time users.

2. Torus Treadmill

2-1. Active locomotion interface using infinite surface

A key principle of an active locomotion interface is to make the floor move in a direction opposite to the direction of the walker. The motion of the floor cancels displacement of the walker in the real world. Such an active floor needs infinite area. We must decide geometrical configuration of an active floor in order to realize an infinite walking area. A closed surface driven by actuators has an ability to create an unlimited floor. We must consider following requirements for implementation of the closed surface:

1) A walker and actuators must be put outside of the surface.

2) Walking area must be a plain surface.

3) Material of the surface must not be stretchable.

Shape of closed surface, in general, is a doughnut with holes. If the number of holes is zero, the surface is a sphere. The sphere is the simplest infinite surface. However, the walking area of the sphere is not a plain surface. A very large diameter is required to make plain surface on a sphere, which restricts implementation of the locomotion interface. A closed surface with one hole is called torus. A torus can be implemented by a group of belts. These belts make plain area for walking. A closed surface with more than two holes cannot make plain walking area. Thus, the torus is the only shape which is suitable for a locomotion interface.

2-2. Implementation of infinite surface

A locomotion device using torus is implemented by a group of belts connected to each other. The Torus Treadmill is realized by these belts. Figure 1 and 2 illustrates mechanical configuration of the Torus Treadmill. Figure 3 shows overall view of the apparatus. The Torus Treadmill employs twelve treadmills and each treadmill is driven by an AC motor. Those treadmills move the walker along the X direction. Power of each motor is 80W and controlled by an inverter. The maximum speed of each treadmill is 1.2m/s.

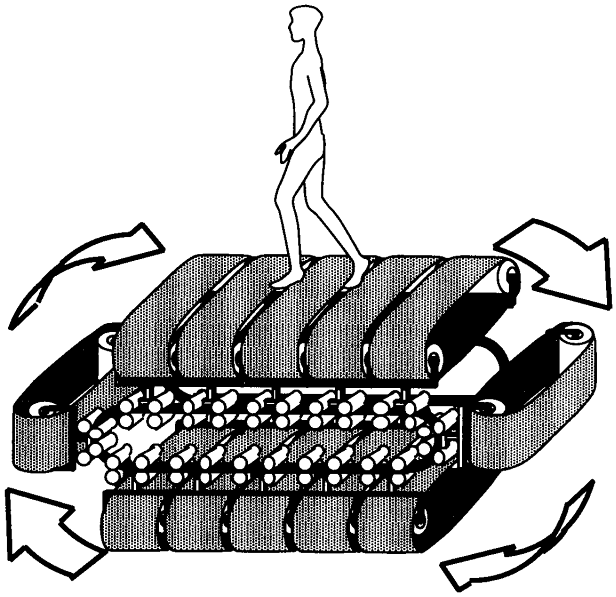

Fig.1 Torus Treadmill (X motion)

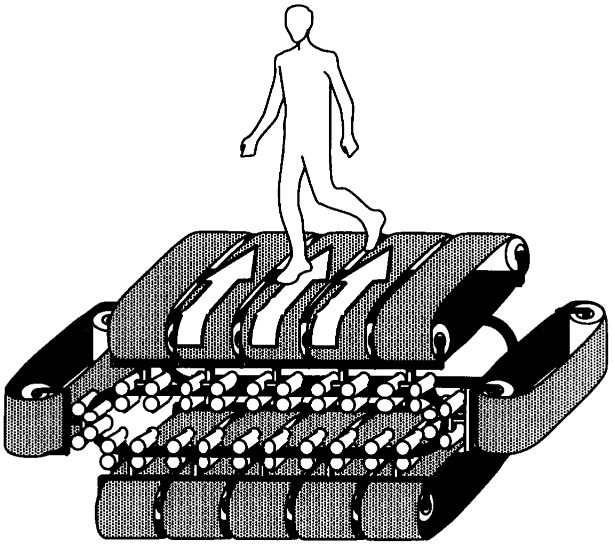

Fig.2 Torus Treadmill (Y motion)

Twelve treadmills are mounted on two endless rails and actuated by four chains. The rails and chains move the walker along the Y direction. An AC motor is employed to drive the chains. Power of the motor is 200W and the maximum speed is 1.2m/s. Width of each belt is 250mm and overall walkable area is 1m x 1m.

A problem of this mechanical configuration is the gap between the belts at the walking area. In order to minimize the gap, we put a driver unit of each treadmill alternatively. The gap is only 2mm by this mechanism.

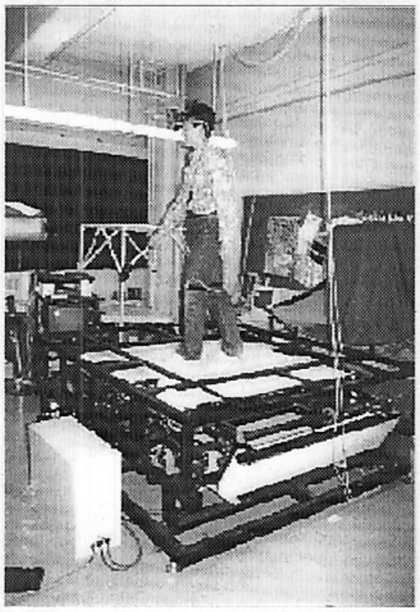

Fig.3 Overall view of the Torus Treadmill

2-3. System configuration of the Torus Treadmill

The overall system of the Torus Treadmill employs two computers: a graphics computer for a real-time image of virtual space and an I/O computer which supervises motors and sensors. These computers are connected by a serial(RS-232C) communication line.

(1) Graphic computer and display

Real-time image of the virtual space is generated by a Silicon Graphics workstation. We use SGI Indigo2 with MAXIMPACT graphics engine. The CPU of the workstation is R4400, which manages model of virtual space. The image on the CRT of the workstation is converted to NTSC standard video signal, and sent to the HMD. We set two windows on the CRT and each image is taken by a video camera. We use a Media Mask (made by Olympus Co.) HMD,which presents stereoscopic image. The liquid crystal display has 512,880 pixels. The effective field of view is 60 degrees(H) X 34 degrees(V). Figure 4 shows a view of the Media Mask.

Fig.4 Media Mask

(2) I/O computer and sensors

The I/O computer supervises the Polhemus sensors and motor drivers for the Torus Treadmill. The I/O computer is a PC with Pentium II 300MHz. We use a magnetic sensor(Polhemus FASTRAK) for body tracker for the walker. Polhemus sensor is connected to RS232C port of the PC. The motor driver unit is also connected to RS232C port of the PC.

(3) Motion tracker

A scene of the virtual space is generated corresponding with the results of motion tracking of the feet and head. The motion of the feet and head is measured by Polhemus FASTRACK. The device measures 6 degree-of-freedom motion. Sampling rate of each point is 20Hz. Two receivers are set at the knees. We cannot put the sensors near the motion floor because a steel frame distorts magnetic field. The length and direction of a step is calculated by the data from those sensors. View point in virtual space moves corresponding with the length and direction of the steps. Overall update rate of the system is 15Hz. Major duration is caused by data transmission from Polhemus sensors to host workstation.

2-4. Control algorithm of the Torus Treadmill

In order to keep the position of the walker at the center of the walking area, the Torus Treadmill must be driven corresponding with the walker. The control algorithm is required to achieve safe and natural walking. From our experience in the Virtual Perambulator project, the walker must not be connected to harness or mechanical linkages. Those devices restrict motion of the walker and spoilt natural walking. Control algorithm of the Torus Treadmill must be safe enough to remove the harness from the walker. At the final stage of the Virtual Perambulator Project, we succeeded in removing the harness using a hoop frame. The walker can freely walk and turn about in the hoop. The hoop supports the walker's body while he/she slides the feet. We introduced the function of the hoop into control algorithm of the Torus Treadmill. We put circular insensitive area at the center of the walking area. If the walker goes out from the area, the floor moves in the opposite direction so that the walker is carried back into the insensitive area.

Figure 5 illustrates basic idea of the control algorithm. Position of the walker is measured by two Polhemus sensors put on the knees. The middle point of these sensors can be assumed to be a central point of the body. Point G represents central position of the walker. We put insensitive area at the center of the walking area. The floor does not move while point G is inside the insensitive area. If point G goes out form the insensitive area , the floor moves so that point G goes back to this area. The insensitive area is a circle whose diameter is 20cm. Distance between point G and the circle determines motor power. Motor power increases in proportion to the displacement of point G from the insensitive area. The active floor performs as a virtual spring which pulls the walker back to the center of the walking area. This control algorithm enables the walker to smooth acceleration and deceleration. The insensitive area removes chattering of the Torus Treadmill. The floor does not move while the walker is turning about at the center of the walking area.

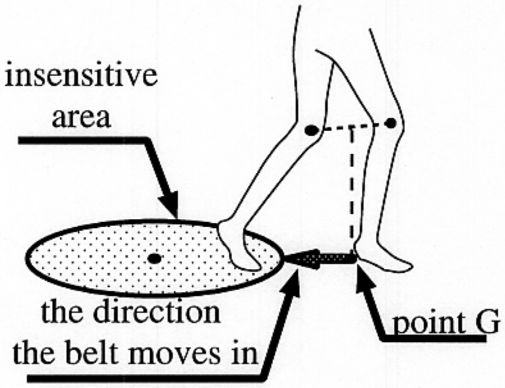

Fig.5 Basic idea of the control algorithm

3. Motion base

The motion base we use employes three sets of linear actuators that can move the operator's chair on itself in some direction and atittude by combining motions about the z, pitch and yaw axes. Each linear actuator is driven by a servo motor. The working range of the motion base in roll and pitch is ±15 degrees and the working range in z axis is ±100 mm. Figure 6 shows overall view of the motion base.

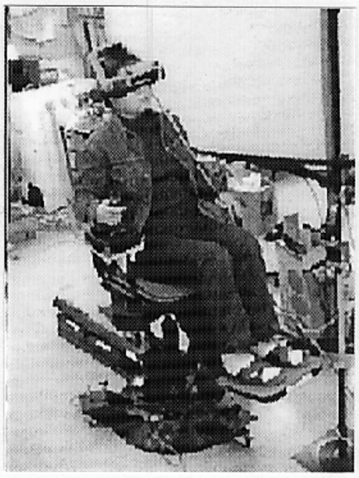

Fig.6 Overall view of the motion base

The operator drives the motion base with a joystick fixed on the arm rest of the operator's chair. Direction of flight is determined by the left/right input, and speed is determined by back/forward. The accelaration of flight is displayed by inclination of the operator's chair to make the operator feel his/her own gravitational force as the accelaration in virtual space(Figure 7).

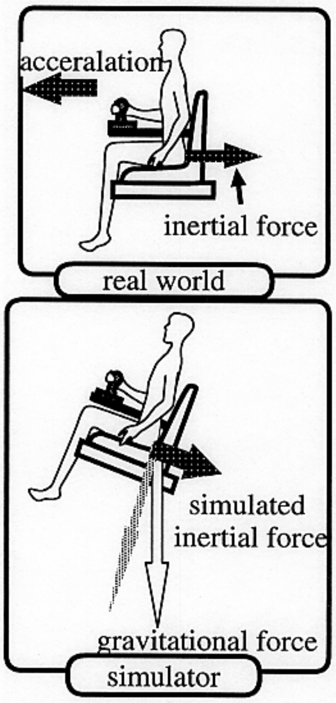

Fig.7 Inclination of the operator's chair(pitch)

The left/right input with the forward input makes the operator turn toward left/right in virtual space. The left/right input without the forward input makes no movement in virtual space. This behavior is the same as vehicle's. The operator's chair is inclined to right/left to simulate the centrifugal force in the period of turning left/right(Figure 8).

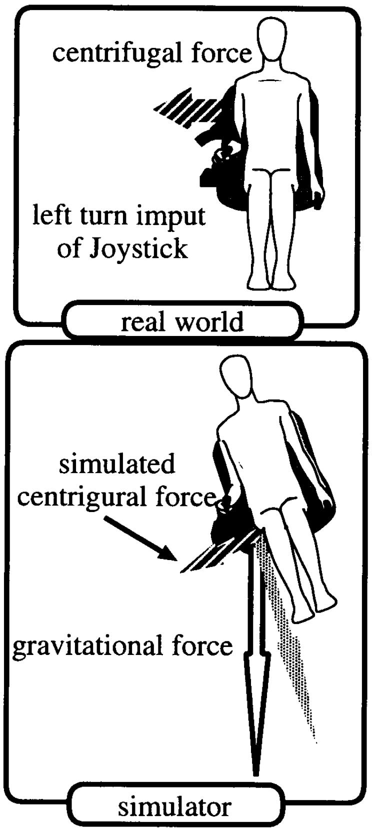

Fig.8 Inclination of the operator's chair(roll)

4. Experiment

4-1. Method

4-1-1. Test space

Navigation performance is quantitatively measured using the locomotion interface. The test space of the experiment is a virtual grass-covered plain. The plain was surrounded by trees. Distance between the center of the plain and trees is 50m. All trees have same shapes, thus no landmarks is included in the space. Grass and trees are displayed using texture mapping. Two cone-shaped target objects are set on the plain. Subjects are asked to travel from the starting point to the first target object watching the CG image by HMD. Then the subjects turn about and travel to the second target object. After the subjects finished traveling, they are teleported to the starting point and the target objects disappear. Then they are asked to travel to the place where the target objects were placed.

This method has an advantage in robustness in quantitative study. It has been discussed that method of measurement of human spatial recognition performance have problems (Darken, et al., 1998). Verbal report and map drawing tend to be biased due to individual difference. The method of path reproduction is expected to be free from such bias.

4-1-2. Procedure

Active area of the current prototype of the Torus Treadmill is 1m X 1m, by which width of the step of the walker is limited to 30cm. Actual speed of treadmills is 1.2m/s. Those mechanical limitations oblige the walker to walk slower than natural walking. First-time users of the system are told about this limitation before they experience it. Subjects practiced walking on the Torus Treadmill before the experiments. They got used to it in two to five minutes. They didn't wore safety harness.

In order to examine the effect of proprioceptive and vestibular feedback, following three locomotion modes are set for the experiments:

mode 1) Traveling by walking
mode 2) Traveling by motion base
mode 3) Traveling by pure joystick operation

Direction of flight is determined by the left/right input, and speed is determined by back/forward input. The maximum flight speed is 1.2m/s, which is same as that of the Torus Treadmill. The subjects practiced operation of the joystick for two or three minutes. Figure 9 shows top view of the bent path. Length of each leg is 5m. We prepared four pattern of bent path(theta1=30deg and 60deg, theta2=90deg and 120deg). These patterns are randomly displayed to the subjects.

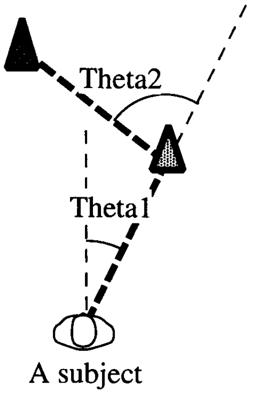

Fig.9 Top view of the bent path

4-1-3. Subjects

The subjects of the experiments are 18 university students(11males, 7females). These subjects are devided into three groups according to the three locomotion modes. Six subjects tried one of the three locomotion modes. Subjects of the Torus Treadmill are first-time users. Subjects ranged in age from 21 to 26 years and had normal or corrected-to-normal vision. They voluntary participated in the experiment.

4-2. Results

Trajectories of the subjects were recorded and distance between correct position of the target object and reproduced position is measured from the data. Figure 10 shows the mean total error distance of three locomotion modes. Error bars represent one standard error of the mean.

Comparing three locomotion modes, mean error distances of Torus Treadmill mode is lower than those of other modes. ANOVAs(alpha value = 0.05) on total mean error distance show significant differnce between Torus Treadmill mode and others(between Motion base mode: p=3.26E-15, between Joystick mode: p=1.2E-11).No significant difference is detected between Motion base mode and Joystick mode in total data.

According to more detailed data analysis, error of Motion base mode is in-between that of Torus Treadmill mode and of Joystick mode. Figure 11 shows mean error distances at the middle point and the final point. At the middle point, mean error distance of Motion base is smaller than that of Joystick mode(p=0.0014). Significant difference is not detected between Motion base mode and Torus Treadmill mode at the middle point, however at the final point significant difference is not detected between Motion base mode and Joystick mode(between Torus Treadmill mode: p=1.17E-09).

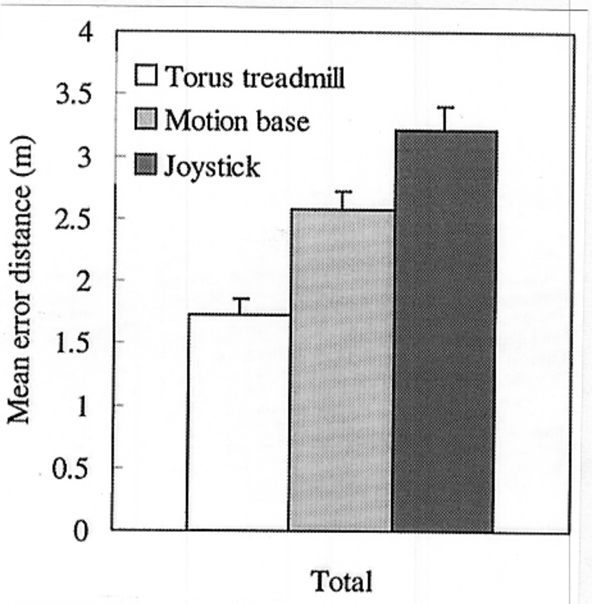

Fig.10 Total mean error distance

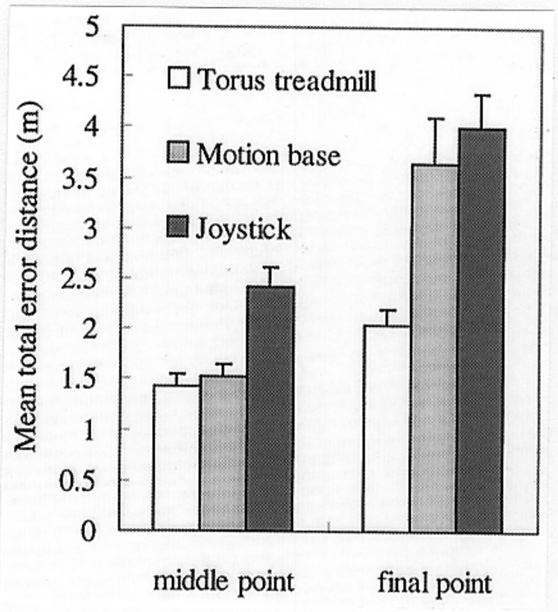

Fig.11 Error distance at middle and final point

4-3. Discussion

The result of the experiment shows that mean error distance of Torus Treadmill mode is constantly smaller than that of other modes. This finding indicates that proprioceptive feedback improves path reproduction performance.

There is no significant difference between the result of Torus Treadmill mode and that of Motion base mode at the middle point but mean error distance of Motion base mode incleases drastically at the final point. The reason why mean error distance of Motion base mode fluctuates is that the orientation performance in Motion base mode directly depends on the amount of turn angle. Figure 13 shows the orientation performance of three modes. When turn angle is small, orientation performance in Motion base mode is as good as that of Torus Treadmill mode. When turn angle grows large, however, orientation performance decreases. Car drivers often use landmarks while turning a tight corner. It is necessary to realize high travel performance in motion base in virtual space that some landmarks are effectively displayed.

Significant difference between error of Motion base mode and that of Joystick mode of middle point shows that vestibular feedback from chair inclination is effective in loose turn.

Difference between Torus Treadmill mode and Joystick mode is highly significant in orientation performance. The error angles of Joystick mode averaged in 150% of that of Torus Treadmill mode constantly. It has been suggested that proprioceptive feedback improves orientation performance. Bakker, Werkhoven, and Passenier(1998) reported that the most accurate turn performance was found when subjects used their legs to turn about. Chance et al.(1998) reported that Real Turn mode performed better than Visual Turn mode for path integration tests. Our results support these findings.

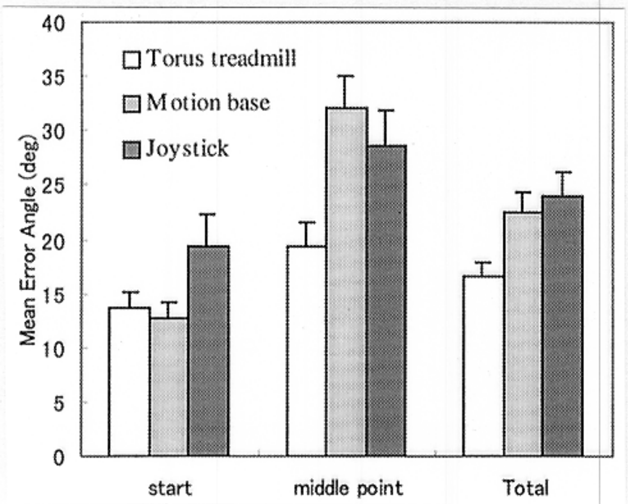

Fig.12 Error angle

5. Conclusion

The basic finding of this research was a difference in performance between the three locomotion modes, showing that proprioceptive information provided by the Torus Treadmill contributes to the ability of path reproduction. The result shows that the best locomotion mode is walking. Vestibular information provided by the motion base increases rotation performance in loose turn. Performance of pure joystick operation is lower than other two modes.

The secondary finding was that usability of the Torus Treadmill for first-time users. All subjects completed the experiments easily. None of the subjects suffered from unstableness while walking or changing direction, although they didn't wore safety harness. The control algorithm succeeded in smooth walking.

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