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Verification of necessity of equivalent gravity in telexistence with scale conversion for utilization of humanoid small robot

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Abstract

According to the concept of telexistence, even telexistence with scale conversion requires control of a robot to maintain the same attitude as that of the operator. However, a mismatch arises between the posture of a person and that of a robot because gravity between the operator and the robot is not subjectively equivalent. Our previous research demonstrated the motion of standing from a sitting position in telexistence with scale conversion using a dynamic control method, which can subjectively achieve the equivalent gravity condition between operator and robot. Acceleration in the forward direction is required to move from a standing position to walking at a constant speed. However, the moment compensation device does not consider the motion that produces acceleration in the forward direction. In this research, we achieve the equivalent gravity state without using a moment compensation device and verify the feasibility of generating walking motion from a standing position.

CCS Concepts

• ***Embedded and cyber-physical systems*** → *Robotic control;*

1. Introduction

When working at a dangerous site, it is important to ensure a secure work environment. One solution is the concept of telexistence, in which people share their senses and movement with a remote humanoid robot to achieve remote operation while feeling as if they are in the same location [Tac13]. Various studies have investigated telexistence. The telexistence system "TELESAR" succeeded in loading blocks and hitting table tennis balls [TY03], while "TELESAR V" can convey not only visual and auditory sensations but also tactile and temperature sensations of hand touching [FFK*12].

Numerous remote robots, such as car-type robots that run with crawlers and snake-type robots, exist far from humanoids but are expected to be useful at various sites. However, these robots cannot perform work, although they can perform photography using cameras; thus, they are not versatile.

If remote operation with telexistence is performed using a humanoid robot, all types of work that can be performed by human beings can be executed; thus, the robot is considered extremely versatile. The acquisition of a special maneuvering method is unnecessary because the movement capacity acquired in nature can be fully utilized and work that requires immediate evaluation is manageable. In other words, the operator can perform naturally employing human intelligence. Furthermore, if the robot is smaller than natural human size, it can be used in spaces too narrow for humans to enter.

In summary, if telexistence with scale conversion can be applied to a small humanoid robot in the field, where the problem of human size cannot be solved, then human ability can be considered.

However, for telexistence with scale conversion, gravity is not subjectively equivalent between the operator and the robot, leading to a mismatch arising between the posture of operator and robot.

Therefore, our previous research focused on the subjective inequality of gravity, which is dominant in the dynamic behavior of the robot and proposed a solution to the problem using a dynamic control method that can subjectively reproduce the equivalent gravity condition. We achieved the equivalent gravity condition by using a control device that compensates for the moment around the ground contact point of a robot's standing leg and succeeded in raising the robot from a seated position.

In this study, instead of using a moment-compensation device, we aim to achieve the equivalent gravity condition by changing this variable according to the gravitational acceleration of the robot to perform a walking motion from a standing position.

2. Problems and solutions in telexistence with scale conversion

In telexistence, even if a robot follows the movement of an operator perfectly, if the environment is different between the operator and the robot, differences in physical constants such as gravity and frictional force may cause inconsistencies in behavior between the two.

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For example, when an operator is on Earth and a robot of equivalent size walks on the Moon, even if both were to fall from the same posture at the same time, the person will quickly fall whereas the robot will fall slowly because the gravity on the Moon is approximately 1/6 the gravity on Earth. Astronauts must become accustomed to such a gravity difference. To replicate this gravity environment on Earth, previous research can be used; for example, inclining the walking plane for astronaut training to reduce effective gravity [Spa70] or hanging astronauts from the ceiling [GTK99]. However, these techniques represent "dynamical similarity" rather than "geometical similarity."

Geometical similarity has been thoroughly discussed in terms of the scale conversion of avatar height and its binocular distance (BD) in the virtual world [KI17]. The results of that study revealed that relevant daily objects surrounding the participant in the virtual environment reduce the redundancy as to whether the person feels larger than usual or the world feels smaller than usual. BD is a representative parameter that produces scale conversion telexistence using geometrical similarity. Once BD is fixed in the virtual environment, distance perception can be affected because a change in the vergence angle results in a slight change in the real binocular distance [UMTK94]. These two studies involve no dynamical parameter that satisfies the dynamical similarity of scale conversion telexistence.

In the case of telexistence with scale conversion, in which operator and robot sizes are not equal, even if the operator and robot walk in an environment where all physical constants are equivalent between the robot and the operator, the behaviors of the two are different.

For example, if an operator walks using a robot built to 1/n scale of the operator in telexistence with scale conversion, we assume that acceleration is applied to the operator and that the robot is accelerated in the translational direction due to gravity acceleration and self-motion, as shown in Figure 1. The blue arrow represents acceleration in the translational direction and the red arrow represents gravitational acceleration. The acceleration in the translational direction of the robot is 1/n times that of the operator, whereas the acceleration of gravity does not change. The walking motion is assumed to be constant for 1 min; it is defined as the motion due to gravity acceleration of the rigid body and acceleration in the translational direction.

When one leg is a standing leg and the other leg is a free leg, a moment is generated around the grounding point of the standing leg. Gravity is dominant in the dynamic behavior of the robot, as shown in the inverted pendulum model. Assuming that acceleration in the translational direction is sufficiently smaller than gravitational acceleration and can therefore be neglected, the 1/n scale robot falls around the ground point with a faster angular acceleration than that of the operator. At this time, the gravity felt by the operator due to visual information obtained by the robot is n times higher than usual.

The gravity felt at this time is defined as "subjective gravity," and n times the gravity is defined as "the subjective gravity is n times." If we achieve telexistence with scale conversion, which requires realistic feeling, it is necessary to match the angular acceleration around the ground point of the person and the robot. We define the condition required to achieve telexistence with scale conversion as "the equivalent gravity condition." This means controlling the robot to control the angular acceleration around the grounding points of the operator and of the robot and matching the subjective gravity felt by the operator as n times the usual gravity.

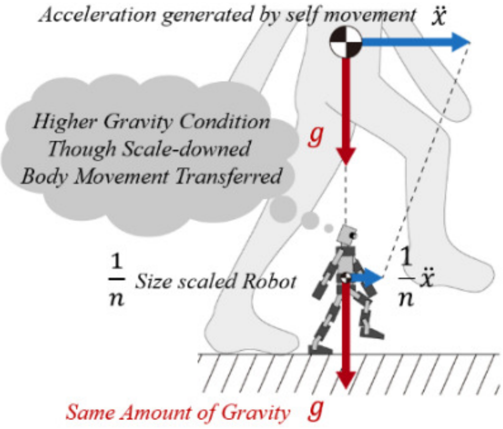


Figure 1: *Subjective difference in gravity between operator and robot*

For "the subjective gravity is n times" state, problems arise when walking during telexistence. The human senses are sight, sound, smell, taste, and touch. Vision is important in telexistence because it plays an important role in maintaining balance when walking and standing. Not only central vision but also peripheral vision plays an important role in maintaining posture while walking [BWK99]. When the world in front of our eyes fluctuates, and optical flow occurs, attitude reflection results [AHM15]. If this optical flow is strong, a phenomenon called vection occurs, whereby the operator feels as if they are moving and may actually move [TS15]. Therefore, to prevent the excessive occurrence of optical flow, it is necessary to match the posture of the operator and robot in scale conversion telexistence.

3. Hypothesis for operator and robot behavior

Here, we analyze the behavior of the operator and robot from static and dynamic viewpoints, which proves that the angular accelerations of the robot and the operator can be matched by achieving the equivalent gravity state through setting the gravity acceleration of the robot to 1/n times that in telexistence with scale conversion using the 1/n scaled robot of the operator. To simplify the problem, we consider that the operator and the robot are bars with uniform mass distribution. Walking is divided into periods of minutes, and the motion of a certain period is regarded as movement of a rigid body.

3.1. Static behavior model

Consider the static behavior of an operator and a robot. If the operator and the robot are regarded as rigid bodies, the force applied to each is expressed as shown in Figure 2.

The gravity acceleration is g, the human mass is m_H, the normal force received from the floor is N_H, the translational force is F_{1H}, the friction force received from the floor is F_{2H}, and the translational acceleration is $\ddot{x}_H$. Similarly, for the robot, the mass of the robot is m_R, the friction force received from the floor is F_{1R}, and the translational acceleration is $\ddot{x}_R$. N and mg are balanced, and F_2 does not occur unless a person drags his foot.

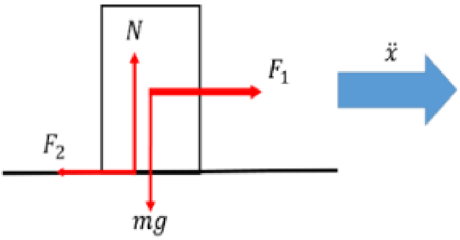


Figure 2: *Model of operator and robot static behavior*

Therefore, the operator and the robot move forward with an acceleration of $\ddot{x}_R = F_1/m$ based on the equation of motion. In telexistence with scale conversion, walking is assumed to start from time t_1 in a stationary standing state and attain a constant walking speed at time t_2. If the distance traveled by the operator is x_H and the distance traveled by the robot on the $1/n$ scale is x_R, the following relationship holds.

$$x_H = n x_R \tag{1}$$

For x_H and x_R, if the initial velocities of the person and the robot are both 0, the following equations hold.

$$x_H = \frac{1}{2}\ddot{x}_H (t_2 - t_1)^2 \tag{2}$$

$$x_R = \frac{1}{2}\ddot{x}_R (t_2 - t_1)^2 \tag{3}$$

From equations (1-3),

$$\ddot{x}_H = n\ddot{x}_R \tag{4}$$

From equation (4), the acceleration of the 1/n scale robot is 1/n times the operator's acceleration.

3.2. Dynamic behavior model

Consider the dynamic behavior of the operator and the robot. If the operator and the robot are regarded as rigid bodies, the force applied to each is expressed as shown in Figure 3. F_1 is the component of gravity, and F_2 is the component of acceleration caused by translational force.

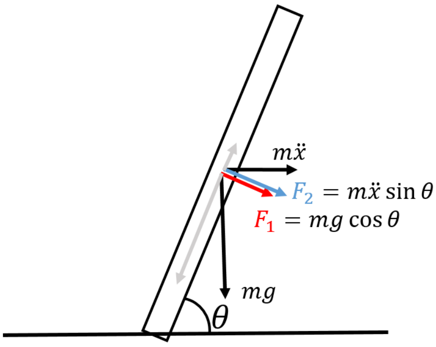


Figure 3: *Model of operator and robot dynamic behavior*

We define the size and mass of the operator and the angle between the floor and the operator, shown in Figure 3, as l_H, m_H,and θ_H, respectively. Similarly, we define the size and mass of the robot and the angle between the floor and the robot, shown in Figure 3, as l_R, m_R, and θ_R, respectively. The relationships between the moment of inertia and angular acceleration around the contact points of the operator and of the robot are shown in equations (5) and (6), respectively.

$$\frac{1}{3} m_H {l_H}^2 \ddot{\theta}_H = \frac{1}{2}(F_{1H} + F_{2H}) l_H \tag{5}$$

$$\frac{1}{3} m_R {l_R}^2 \ddot{\theta}_R = \frac{1}{2}(F_{1R} + F_{2R}) l_R \tag{6}$$

We divide (6) by (5) and reorganize.

$$\frac{\ddot{\theta}_R}{\ddot{\theta}_H} = \frac{(F_{1R} + F_{2R}) m_H l_H}{(F_{1H} + F_{2H}) m_R l_R} \tag{7}$$

We then assume that the ratio between the height and mass of the operator and of the robot can be expressed as follows:

$$l_H : l_R = n_1 : 1 \tag{8}$$

$$m_H : m_R = n_2 : 1 \tag{9}$$

Therefore,

$$l_H = n_1 l_R \tag{10}$$

$$m_H = n_2 m_R \tag{11}$$

We assume that the specific gravity of the robot is equivalent to the specific gravity of the operator.

$$n_2 = {n_1}^3 \tag{12}$$

Therefore,

$$m_H = {n_1}^3 m_R \tag{13}$$

As shown in Figure 3,

$$F_{1H} + F_{2H} = m_H g cos\theta_H + m_H \ddot{x}_H sin\theta_H \tag{14}$$

$$F_{1R} + F_{2R} = m_R g cos\theta_R + m_H \ddot{x}_R sin\theta_R \tag{15}$$

Substituting equations (4), (10), (13), (14), and (15) into equation (7), the right side becomes the following

$$\frac{(m_R g cos\theta_R + m_R \ddot{x}_R sin\theta_R){n_1}^3 m_R n_1 l_R}{({n_1}^3 m_R g cos\theta_H + {n_1}^3 m_R n_1 \ddot{x}_R sin\theta_H) m_R l_R} \tag{16}$$

When equation (16) is reorganized, it becomes equation (17).

$$\frac{\ddot{\theta}_R}{\ddot{\theta}_H} = \frac{n_1 g_R l_R cos\theta_R + n_1 l_R \ddot{x}_R sin_R}{g l_R cos\theta_R + n_1 l_R \ddot{x}_R sin\theta_R} \tag{17}$$

According to equation (17), when considering the translational force, the ratio of the angular acceleration of the operator to that of the robot is not proportional to the reciprocal of the height ratio. However, by setting $g_S = g/n_1$, the ratio of the angular acceleration of the operator to that of the robot does not change.

If the initial posture of the robot is equal to the initial posture of the operator from the global coordinate system, the equivalent gravity condition can be generated by setting the gravity acceleration of the robot to g/n_1.

4. Walking Experiment with Biped Humanoid Robot

4.1. Biped Humanoid Robot for Telexistence

In the experiment, we employ a robot based on the KHR-3HV (Kondo Kagaku Co., Ltd.) shown in Figure 4. The height of the robot is 44 cm, which is 1/4 that of a person with a height of 176 cm. The waist and arms of the robot are fixed, and the legs and neck are controlled. The neck and legs of the robot are controlled using the motors of T_R, T_P, T_Y, and T_1 to T_{12} in Figure 4.

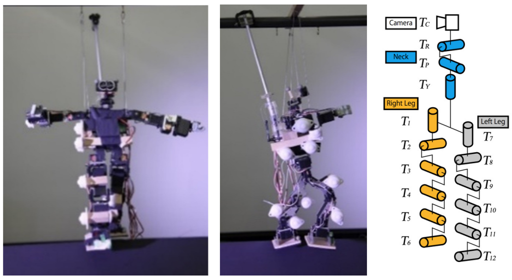


Figure 4: *One-quarter scale slave robot: front view (left), side view (center), and axis definition of degrees of freedom (right).*

The control method of the robot is as follows. We acquire the position and attitude of each leg and head of the operator using OptiTrack (Natural Point) and solve inverse kinematics using this acquired position and posture. We determine the target angle of each joint in the robot's legs and head and enable the robot to follow the movement of the operator.

As the bottom of the foot of the robot does not deform, to avoid deforming the bottom of the foot and shoes, the operator wears shoes with a wooden board attached to the bottom measuring 280 mm from front and back and 260 mm wide, which is four times the scale of the bottom of the robot's foot. This device can prevent an impression of realism in telexistence. As the center of gravity of the robot is behind the centerline of the body to match the position of the center of gravity, the operator carries a backpack with a weight of 6458 g.

To acquire feedback from the robot, the operator obtains images from the head camera of the robot with Oculus (DK 1). The camera uses OV 5680 (e-CAM) and transmits video with a delay of 1 line as an allowable design value of less than 1 frame by FPGA Zylinx Zynq (Zed Board).

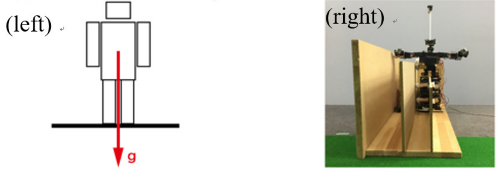
As shown in Figure 5, the equivalent gravity condition is achieved by tilting the robot until the gravitational acceleration that is vertically applied to the floor, as seen from the robot, becomes 1/4 times the gravitational acceleration on Earth. From equation (18), the angle at which the board is tilted is approximately 76°. In the 1960s, NASA conducted a simulation experiment to reduce the influence of gravity received from the Earth to one sixth by tilting the floor by 80°, thus reproducing the same gravity environment as the moon [Spa70].

$$cos^{-1}\frac{1}{4} \approx 76^\circ \tag{18}$$

As shown in Figure 5, the robot is placed on the equipment. The right side of the robot's upper body, the right side of the left foot, and the right elbow are in contact with the board via casters. By obtaining a normal reaction from the board, the gravity acceleration component shown by the gray vector in Figure 5(b-left) is canceled. Attaching casters reduces friction from the side applied to the robot as much as possible and restrains the movement of the robot within the sagittal plane. As shown in Figure 4, the two casters are fitted on the left foot table, two casters are fitted on the right foot table, one caster is fitted on the back of the left foot, and three casters are fitted on the right side of the waist. Casters are also attached to the right elbow to support the upper body.

It has been confirmed that the robot slides smoothly within the equipment due to the casters under both the four times gravity condition and the equivalent gravity condition. Under the four times gravity condition, an experiment is also performed without tilting the experimental device, as shown in Figure 5(a).

(a) Four Times Gravity Condition



(b) Equivalent Gravity Condition

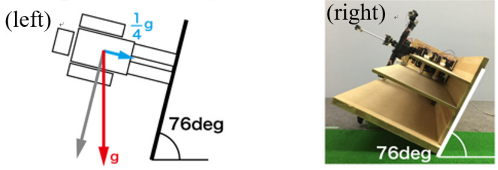
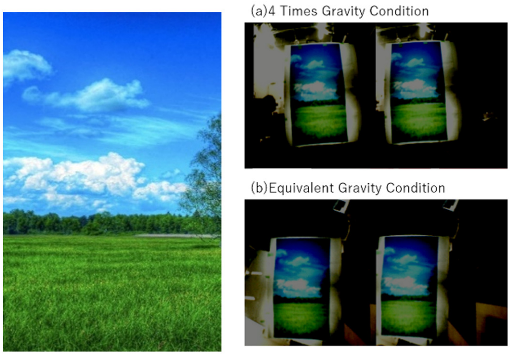


Figure 5: *Robot and the experimental device under (a) the four times gravity condition and (b) the equivalent gravity condition.*

Large-format printed landscape paintings shown in Figure 6 are installed at the tip of the line of sight of the robot. Under the four times gravity condition, the landscape painting is installed in the direction of Figure 6 (left). For the equivalent gravity condition, the landscape painting is installed at 76°, in the same orientation as the robot. Even if the conditions change, the operator can view the landscape painting in the same manner, and the operator can identify both the sky and horizon.


(a)4 Times Gravity Condition

(b)Equivalent Gravity Condition

Figure 6: *Landscape painting (left) and first person views under each condition (right).*

4.2. Procedure

When maneuvering using telexistence with scale conversion begins for a person who is stationary with respect to a small robot in a standing position, the robot moves slightly and stands again while maintaining a standing posture. The walking movement is initiated with the robot in a state of telexistence, again from the stationary state, and set as one trial until the robot falls over. The robot does not completely fall over because it performs the walking motion within the device; therefore, it is assumed to fall when the side of the robot is caught on the device.

In both the equivalent gravity condition and the four times gravity condition, trials were performed five times. For both conditions, the subject used their left foot for the first step only for the fourth trial; for the remaining trials, the subject stepped out with the right foot for the first step. During the trial, the subjects received only visual information from the robot as feedback; the final state of the robot and the images of the subject and the robot were observed at the end of each trial. The subject was a male 175 cm tall weighing 64 kg. Figure 7 shows the operator and robot during a trial.

5. Results and Discussion

For the equivalent gravity condition, in the third and fourth trials, both the operator and the robot walked two steps, and the robot tripped when it attempted to take a third step. In the remaining three trials, when the person took the first step, the robot toppled backward before its foot touched the ground. In the remaining three trials, the robot fell backward before the first footstep of the operator made contact with the ground.

Under the four times gravity condition, in the fourth and fifth trials, the first step of the robot contacted the ground then the robot fell forward. In the remaining three trials, the robot had already fallen when the first footstep of the operator made contact with the ground.

Figure 7: *Conditions of the operator and robot during one trial*

As well as determining whether the robot walked successfully using an animation of the experiment, we also analyzed the head position of the robot to consider whether the walking motion was successful. Figures 8-11 show the positions of the operator's head and left foot (top), the positions of the robot's head and left foot (second top), the angle formed between the operator and robot and the floor (third top), the angular velocity (fourth top), and angular acceleration (bottom) during the trial.

The graph of angular velocity was produced by differentiating the angle curve once with respect to time. The graph of angular acceleration was produced by differentiating the curve of angular velocity once with respect to time.

For Figures 8-15, the uppermost panel shows the position of the "human" head and the position of the left toe. The horizontal axis of this first stage represents the position [mm], and the vertical axis represents height [mm]. The position of the head and toe at the beginning of the experiment is represented in blue. It is then shown in yellow and red as the experiment time proceeds. The position of the head connected by a line and the position of the left toe represent the same time.

In contrast, panel (b) of Figures 8-15 shows the position of the head of the "robot" and the position of the left toe, with all other aspects the same as the first stage. The height of the head position and the position of the left toe of the robot are notably different under the equivalent gravity condition and four times gravity condition because the robot lies within the apparatus under the equivalent gravity condition. The horizontal axis of panels (c), (d), and (e) of Figures 8-15 represent time and the vertical axes represent angle, angular velocity, and angular acceleration, respectively. In addition, red denotes the robot and blue denotes the human.

Figure 8 presents the head trajectories of the robot during successful walking under the equivalent gravity condition. There is little movement of the robot's head in the vertical direction and only slow movement in the forward direction. In contrast, Figure 9 shows the head trajectory of the robot at the time of failed walking under the four times gravity condition, which reveals that motion of the robot's head is large in the vertical direction and relatively fast in the backward or forward direction. Similarly, Figure 11 shows robot head trajectories for successful walking under the equivalent gravity condition and Figure 10 shows robot head trajectories for failed walking under the equivalent gravity condition. From these, we infer that the robot can perform a stable walking motion. From Figures 12-15, we infer that the robot is instantly overturned. This trend applies to all graphs.

We now consider the change in operator behavior according to the vision obtained from the robot. Regarding the operator's head position, as indicated by Figure 12 and Figure 13, the operator moves his head forward when the robot falls behind; similarly, the operator lifts his head when the robot falls forward. When the robot begins to collapse, the operator behaves in the direction that prevents collapse. Therefore, this finding infers that vision greatly affects the behavior of the operator in telexistence with scale conversion. As an example of the important role of vision with regard to balance, when the world in front of a person sways, they feel as if they are moving [Gib94]. If the direction of travel is visually distorted, a person feels like they are walking straight even though there is actually a slight bend in the walking direction [MBN*16]. Therefore, vision is key for walking.

Under the four times gravity condition, the robot falls behind only once. We compare the graph at this time (Figure 15) with the graph when the robot falls behind under the equivalent gravity condition (Figure 14). The operator's head moves sharply in the downward direction. We suggest that this is because, under the four times gravity condition, the robot collapses quickly and large optical flow is experienced by the operator, enabling them to react reflexively. Conversely, under the equivalent gravity condition, the optical flow is small, so the operator cannot react reflexively. We will examine how this phenomenon affects walking.

6. Conclusions

In this study, we verify the feasibility of generating walking motion from a standing position on the sagittal plane in telexistence with scale conversion if the equivalent gravity state is achieved.

Acknowledgments

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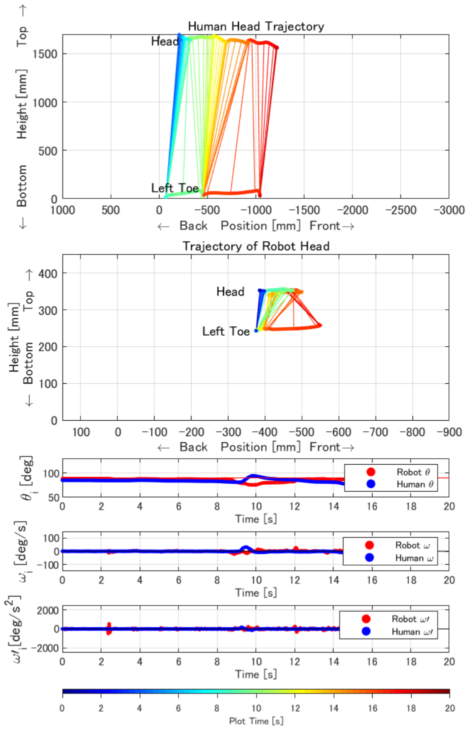

Figure 8: *Successful walking under the equivalent gravity condition (Trial #4).*

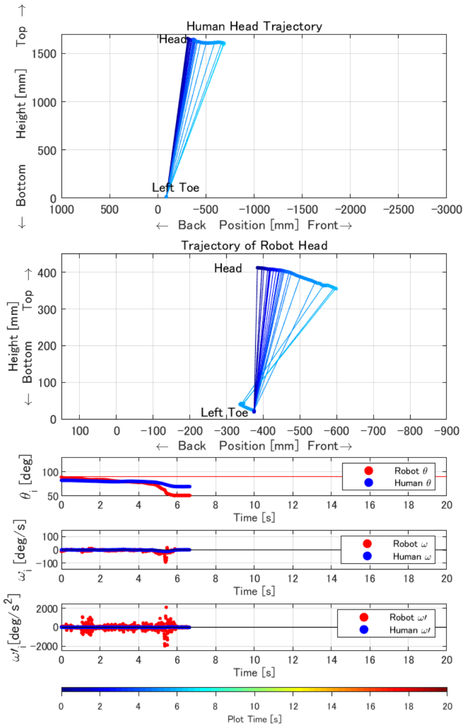

Figure 9: *Failed walking under the four times gravity condition (Trial #8).*

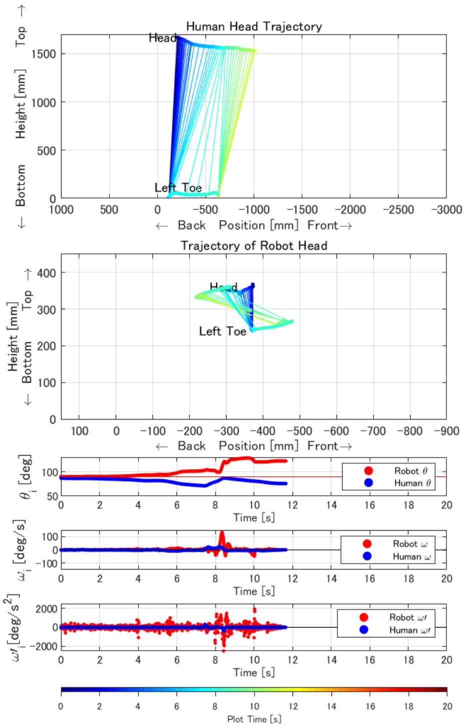

Figure 10: *Successful walking under the equivalent gravity condition (Trial #1).*

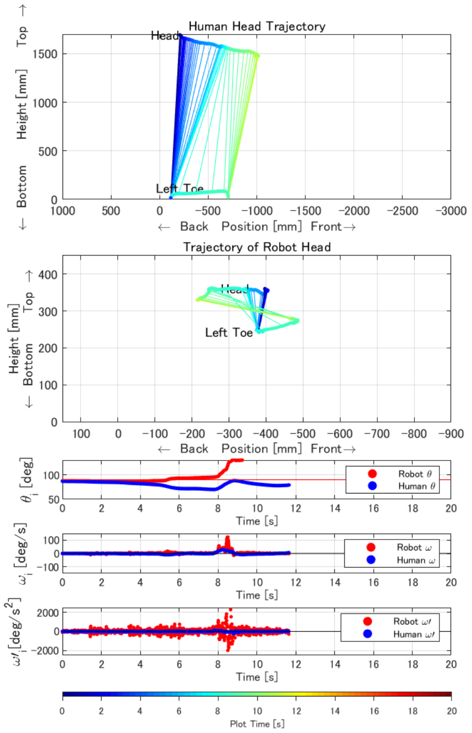

Figure 12: *Change in operator behavior when the robot falls behind under the equivalent gravity condition (Trial #2).*

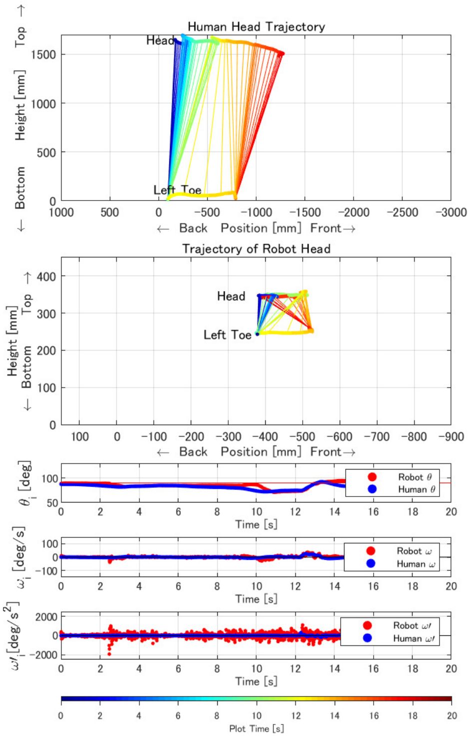

Figure 11: *Failed walking under the equivalent gravity condition (Trial #3).*

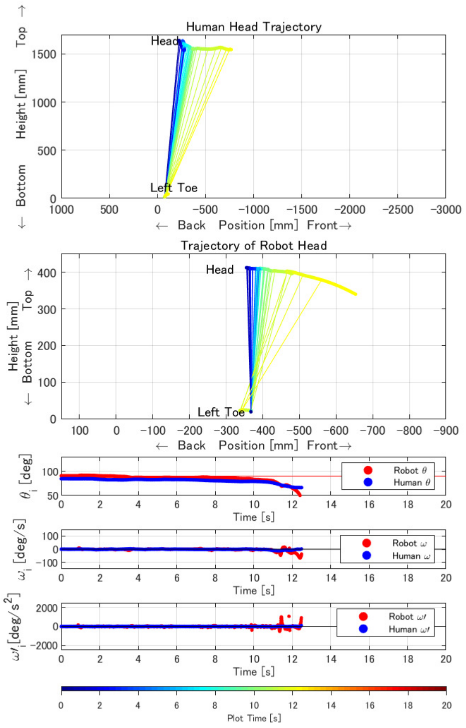

Figure 13: *Change in operator behavior when the robot falls forward under the four times gravity condition (Trial #10).*

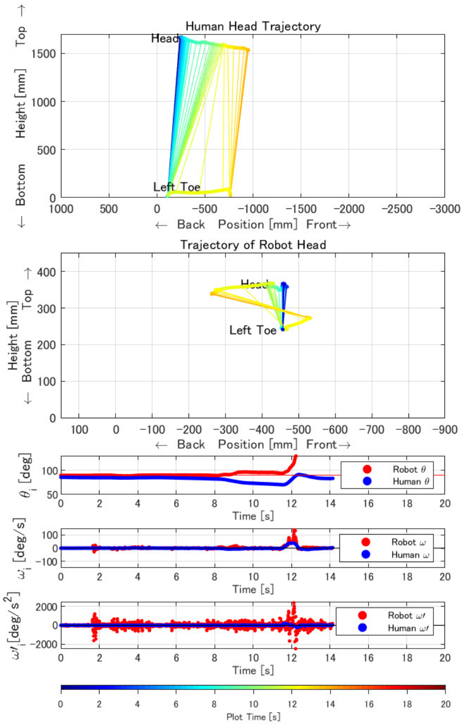

Figure 14: *Change in operator behavior when the robot falls behind under the equivalent gravity condition (Trial #5).*

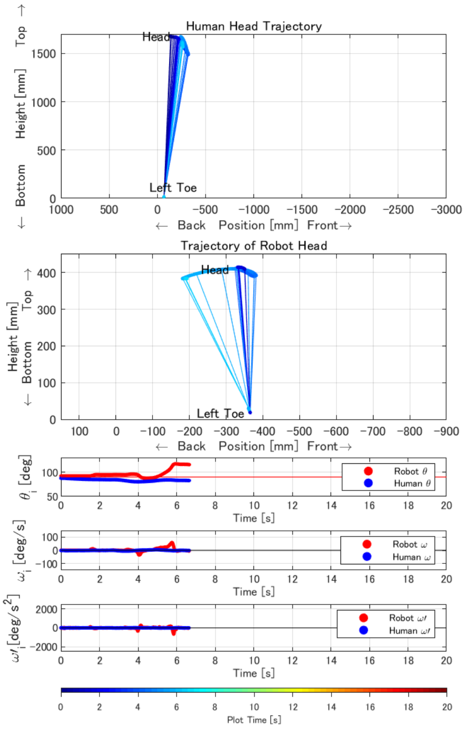

Figure 15: *Change in operator behavior when the robot falls behind under the four times gravity condition (Trial #6).*

References

[AHM15] Assländer L., Hettich G., Mergner T.: Visual contribution to human standing balance during support surface tilts. *Human Movement Science 41* (2015), 147–164. doi:10.1016/j.humov.2015.02.010. 2

[BWK99] Bardy B. G., Warren W. H., Kay B. A.: The role of central and peripheral vision in postural control during walking. *Perception & Psychophysics 6161*, 77 (1999). URL: http://titan.cog.brown.edu/research/ven{_}lab/Publications/BardyWarrenKay{_}CentPeriphPosture{_}P{&}P99.pdf. 2

[FFK*12] Fernando C. L., Furukawa M., Kurogi T., Kamuro S., Minamizawa K., Tachi S., et al.: Design of telesar v for transferring bodily consciousness in telexistence. In *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on* (2012), IEEE, pp. 5112–5118. URL: https://ieeexplore.ieee.org/abstract/document/6385814. 1

[Gib94] Gibson J. J.: The visual perception of objective motion and subjective movement. *Psychological Review 101*, 2 (1994), 318–323. URL: http://doi.apa.org/getdoi.cfm?doi=10.1037/0033-295X.101.2.318, doi:10.1037/0033-295X.101.2.318. 6

[GTK99] Griffin T. M., Tolani N. A., Kram R.: Walking in simulated reduced gravity: mechanical energy fluctuations and exchange. *Journal of Applied Physiology 86*, 1 (1999), 383–390. URL: https://www.physiology.org/doi/abs/10.1152/jappl.1999.86.1.383. 2

[KI17] Kim J., Interrante V.: Dwarf or Giant: The Influence of Interpupillary Distance and Eye Height on Size Perception in Virtual Environments. In *ICAT-EGVE 2017 - International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments* (2017), Lindeman R. W., Bruder G., Iwai D., (Eds.), The Eurographics Association. doi:10.2312/egve.20171353. 2

[MBN*16] Matsumoto K., Ban Y., Narumi T., Yanase Y., Tanikawa T., Hirose M.: Unlimited corridor. In *ACM SIGGRAPH 2016 Emerging Technologies on - SIGGRAPH '16* (New York, New York, USA, 2016), ACM Press, pp. 1–2. URL: http://dl.acm.org/citation.cfm?doid=2929464.2929482, doi:10.1145/2929464.2929482. 6

[Spa70] Spady A. A.: Comments on several reduced-gravity simulators used for studying lunar self-locomotive tasks. In *NASA Technical Note* (1970). URL: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19700016856.pdf. 2, 4

[Tac13] Tachi S.: *Telexistence*. Springer International Publishing, Cham, 2013, pp. 229–259. URL: https://doi.org/10.1007/978-3-319-17043-5_13, doi:10.1007/978-3-319-17043-5_13. 1

[TS15] Tamada Y., Seno T.: Roles of size, position, and speed of stimulus in vection with stimuli projected on a ground surface. *Aerospace medicine and human performance 86*, 9 (2015), 794–802. URL: https://www.ingentaconnect.com/content/asma/amhp/2015/00000086/00000009/art00006. 2

[TY03] TACHI S., YASUDA K.: Evaluation experiments of a telexistence manipulation system. URL: https://www.researchgate.net/publication/220089877_Evaluation_Experiments_of_a_Teleexistence_Manipulation_System. 1

[UMTK94] Utsumi A., Milgram P., Takemura H., Kishino F.: Investigation of errors in perception of stereoscopically presented virtual object locations in real display space. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (1994), vol. 38, SAGE Publications Sage CA: Los Angeles, CA, pp. 250–254. URL: http://journals.sagepub.com/doi/abs/10.1177/154193129403800413. 2