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Development of a Bilateral Control Teleoperation System for Bipedal Humanoid Robot Utilizing Foot Sole Haptics Feedback*

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***Abstract*— Teleoperating bipedal humanoid robots presents unique challenges, including decreased stability and reduced operator presence. This paper addresses these challenges by proposing a method that leverages the operator's inherent sense of stability by feedback from a sole haptics display to operate a bipedal humanoid robot. We developed a bilateral control system that integrates a device replicating sole haptics feedback and provides the operator with feedback on changes in the robot's center of gravity. We conducted operating experiments in the forward-backward direction to evaluate its effectiveness and investigate the effectiveness of sole haptics on robot operation. The results demonstrate that operating with both vision and sole haptics feedback significantly reduces the robot's fall rate by over 56% when disturbances are applied, compared to using only vision feedback. Moreover, operators reported a 21% higher sense of presence with both vision and sole haptics feedback compared to using only vision feedback.**

I. INTRODUCTION

In recent years, significant advancements have been made in teleoperation technology for robots deployed in distant or dangerous environments[1] . Sensory feedback, such as vision, audio, and haptics, plays a critical role in enabling operator to gain a comprehensive understanding of operational environment, thereby enhancing operational performance[2].

Teleoperation of humanoid robots presents two primary challenges: decreased stability and a reduced sense of presence. Currently, humanoid robots used for teleoperation are mostly equipped with wheeled or fixed lower body configurations rather than bipedal types [3], [4]. Therefore, tasks involving inclines or lifting using the lower body are often unfeasible, and these robots are unable to mimic human walking. This limitation stems from the inherent difficulty that bipedal humanoid robots face in maintaining stability, especially on uneven ground, thus hindering practical applications. Moreover, previous studies on whole-body operation of bipedal humanoid robots often use exoskeletons or hand-held joysticks and autonomous balance control, leading to decreased sense of presence of operators [5], [6].

In contrast, human stability sensation integrates various sensory inputs, including vision, vestibular sensation, sole haptics, etc[7]. Humans can discern their center of gravity position by interpreting ground reaction forces through their feet, allowing for continuous adjustments in balance to maintain stability[8].

Therefore, this study proposes two objectives: enhancing the stability of bipedal humanoid robots by utilizing human stability sensation through providing sole haptics feedback to the human operator; and improving the operator's sense of presence by mimicking human balance movements to control their center of gravity.

The paper is structured as follows: Section II introduces the design of a device capable of providing sole haptics feedback and the operation system; Section III describes the control method of the system; Sections IV and V detail the operating experiments conducted to evaluate the effectiveness of the developed device and system, along with investigating the function of sole haptics during operation; Finally, Section VI presents the conclusions and future work.

This study significantly contributes to validating the effectiveness of sole haptics in teleoperating bipedal humanoid robots. It also highlights that accurately providing sole haptics feedback to dynamically changing sole sensation is a critical challenge for future research.

II. SYSTEM OVERVIEW

The overall configuration of the operation system is shown in Fig. 1. Visual information and sole haptic feedback of a small bipedal humanoid robot are relayed to the human operator via display screens and a foot pressure feedback device. In response, the human operator adjusts their feet and other body joints to achieve a stable operation of the standing robot, leveraging their own sense of stability.

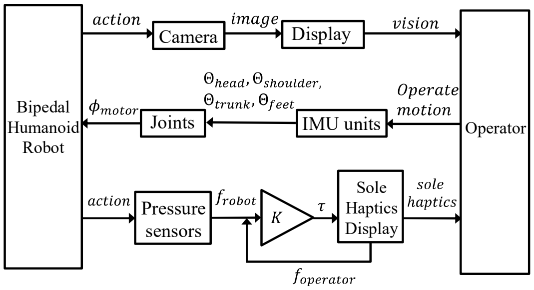

Fig. 1. Configuration of operation system.

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A. *Humanoid Robot Nemo*

A bipedal humanoid robot named Nemo, as shown in Fig. 2, is developed and used for operation. The robot is designed based on human proportions and center of gravity distribution. It consists of 24 servo motors (XM430-W350) distributed throughout its body, providing it with 24 degrees of freedom. Fig. 3 shows an enlarged view of the robot's foot. The foot is designed to mimic the shape of a human foot, dispersing the overall reaction force of each foot across four points: big toe, ball, hypothenar, and heel. Pressure sensors (Flexiforce) are integrated into each point to measure the reaction forces, and rubber protrusions with thickness of 1.5[mm] are inserted at these four points to distribute the foot pressure.

B. *Sole Haptics Display*

Previous studies on replicating sole haptics, including shoe types[9] , virtual floor types [10] , etc., mostly utilizes vibration or electrical stimulation methods. However, operators cannot provide feedback to such types of stimulation. Additionally, most studies typically stimulate only one point on each foot, further limiting the operator's ability to sense changes in the center of gravity. Therefore, we developed a device capable of providing force feedback, as shown in Fig. 4. Linear actuators are positioned at four points on the operator's foot, corresponding to those on the robot's foot. Operators sit or stand on the linear actuators, sensing sole haptics of the robot through stimulation with the linear actuators and operating by pushing back against them.

The linear actuator consists of a linear guide and a ball screw, allowing for vertical motion up to a maximum stroke of 45[mm] through motor (EC-i40) rotation. At the tip of the linear actuator, there is a sensor box containing the pressure sensor, which measure the reaction force of the operator's sole when stimulated. The control method of the sole haptics display is explained in section III.

C. *IMU unit ring*

To achieve intuitive control with minimal constraints, various methods capture the operator's posture. These include using Azure Kinect depth sensor cameras for skeletal structure detection and motion capture systems [11], [12]. However, the former method may inaccurately recognize front-back directions due to skeletal point cloud convergence at a single point, while the latter is known for longer delays. In this study, for accurate angle measurement, minimal delay, and ease of operation, we employ IMU sensor units (BNO055). The sensor is mounted on 3D-printed ring attached to operator's each joint.

III. BILATERAL CONTROL METHODS

For the control method of the operation system, we implemented a bilateral control method which is commonly employed in teleoperation and surgery robots [13], [14], enabling simultaneous control of both force and position of actuators. Fig. 5, Fig. 6 shows the schematic diagram of the bilateral control system configuration. In this case, pressure control works to regulate the motion of linear actuators, allowing the operator to perceive the balance condition of the robot. Meanwhile, the operator adjusts the posture of their feet and body based on their own stability sensation. Position control determines the angle of the motor to replicate the operator's actions. By continuously iterating pressure control and position control at a high-speed loop cycle of 1[ms], the robot is expected to maintain stability during operation, in coordination with the operator. Thus, the system is supposed to be used not only for operating the robot but also for enhancing the operator's stability skills, such as rehabilitation and assisting the elderly[15].

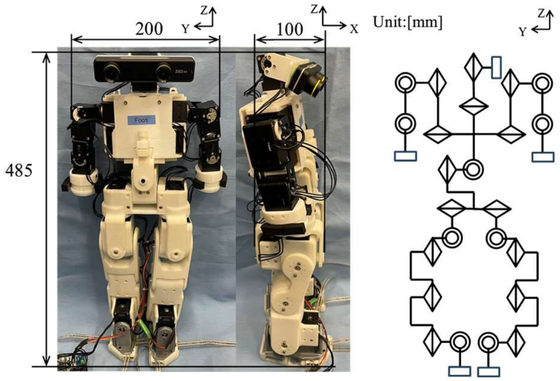


Fig. 2. Humanoid robot NEMO.

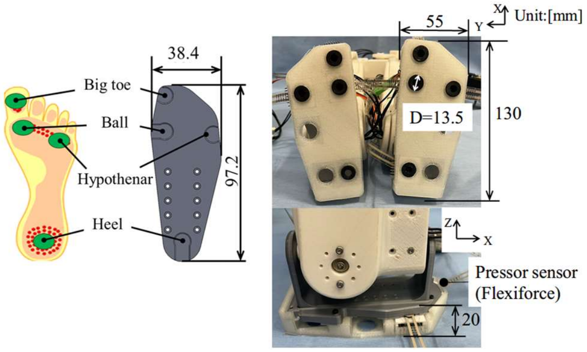


Fig. 3. Foot sole of robot.

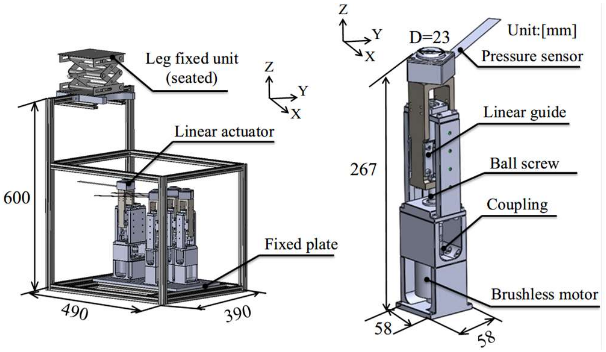


Fig. 4. Configuration of Sole Haptics Display.

A. *Pressure Control*

Green Part in Fig. 6 shows the schematic diagram of the sole haptics replication system configuration. Pressure control is conducted through the following steps: First, measure the sole pressure of robot and operator at four points, using pressure sensors embedded in robot's foot and sensor box of the linear actuators. Then, calculate the output torque value τ of each motor of linear actuator according to equation (1) and (2). The torque value τ is subsequently transmitted to the motor driver, which controls the motor's torque, thereby moving the linear actuators. The equations for pressure control are as follows:

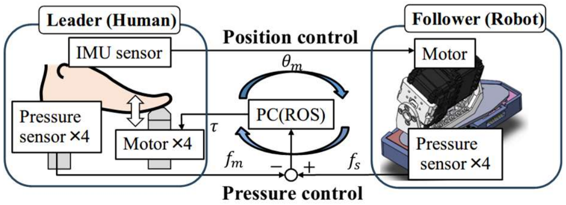


Fig. 5. Schematic diagram of bilateral control system for foot.

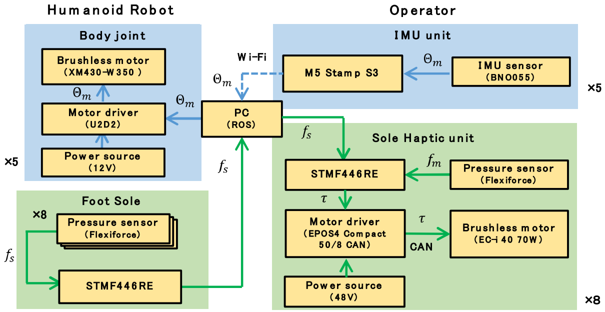


Fig. 6. Schematic diagram of the proposed system.

$$e = f_s - f_m \tag{1}$$

$$\tau = K_p \cdot e + K_d \cdot T_d \frac{de}{dt} \tag{2}$$

Here, f_s represents the pressure of the robot's foot sole, f_m represents the pressure of the operator's foot sole, e represents the deviation, and τ represents the motor torque. K_p, K_d are the feedback gains, which depend on the operator's weight and the sensitivity of their foot sole and may vary across the four points. Manual tuning is necessary to adjust these values appropriately as below: First, gains K_p, K_d are adjusted to ensure consistent pressure at each point, resulting in balanced force perception. Next, the gains are adjusted until clear changes are perceived when shifting the robot's center of gravity. To achieve rapid computation and control of linear actuators, each point is independently controlled by a microcontroller. By measuring the motor encoder, a delay of approximately 5[ms] occurs in the sole haptics replication system, including communication and response delays.

B. Position Control

Along with pressure control, we use IMU sensors to measure the angles of the operator's feet and control the robot's foot angle accordingly. This enables bilateral control at the foot level. Since the motors have encoders to read positions accurately, it is believed to achieve precise angles when inputting target angles, without compliance control as force control. Additionally, to conduct whole-body operation, we apply position control to joints of the operator's head, shoulders, and trunk. These joints are equipped with IMU sensor rings as feet, to determine their angles and control the corresponding motors in the robot. The joints of the robot mapped from the IMU are constrained by angle limits to prevent rotation beyond human joint angles, and other joints are constrained to angles typical of an upright posture. At this stage, we're mainly focusing on controlling movements that cause the robot to tilt forward or backward. Therefore, only joints associated with front-back movements are incorporated at this stage.

IV. EXPERIMENT

We conducted the following operation experiments using the developed system to verify its effectiveness under various conditions, including feedback information, operating speed, and body joints. Due to the complexity of the experimental conditions and factors involved, the experiments were divided into three stages. For better understanding, the varying conditions for each experiment are summarized in Table I. These experiments were approved by the Ethical Review Committee of our institution (2022-215).

TABLE I. CONDITIONS FOR OPERATION EXPERIMENTS

No.	Conditions		
	Operating motion	**Feedback sensations**	**Comparison items**
A	Single-foot	Vision of Operator's view, sole haptics	Speed, feedback sensations
B	Whole body	Vision of Robot's view, sole haptics	Body joints, feedback sensations
C	Whole body	Vision of Robot's view, sole haptics	Disturbances (impact, heavy load), feedback sensations

A. Operating Experiments with Foot Control

To evaluate the effectiveness of the bilateral control system and explore the relationship between feedback information and operating speed, we conducted operating experiments using only one foot (single-foot) under different conditions of feedback sensation and speed. After tuning the sole haptics display, experiments were conducted under the following cases:

- Case 1 (vision only): The operator stood on the ground and observed the robot while tilting it by moving their ankle forward and backward to the maximum angle, attempting to maintain the robot's balance. This was performed at slow, moderate, and fast speeds.
- Case 2 (vision and sole haptics): The operator stood on the active sole haptics display and performed the same operation task as in Case 1 while observing the robot.
- Case 3 (sole haptics only): The operator stood on the active sole haptics display with their eyes covered and performed the same operation task as in Case 1, as shown in Fig. 7.

For each condition, the operator continued to operate the robot for 30[sec]. The experiment was conducted by six operators, who completed a survey evaluating their sense of presence after the experiment, based on personal feedback from the operators.

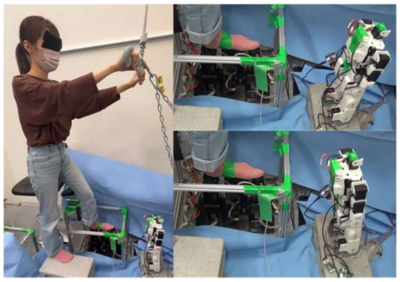


Fig. 7. Operating experiments with foot control.
(Above: tilt to over 5[deg]. Below: return to 0[deg].)

B. Operating Experiments with Whole-Body Control

To validate the effectiveness of the whole-body operation system and investigate the relationship between feedback sensations, we conducted operating experiments under different conditions of feedback sensations. After tuning the sole haptics display, experiments were conducted under the following cases:

- Case 1 (vision only): The operator stood on the ground and watched the display showing robot's view while tilting it by moving whole body joints forward and backward to the maximum angle at moderate speed, attempting to maintain the robot's balance.
- Case 2 (vision and sole haptics): As shown in Fig. 8, the operator stood on the active sole haptics display and perform the same operation task with whole body as in Case 1 while watching the display. When operating with the sole haptics display, the operator was allowed to hold a handrail with one arm for safety while using the other arm to operate the system. To ensure consistency in the left-right direction, both arms of the robot were synchronized to match the angle set by the operating arm, and the operator was instructed to maintain the same angle for both feet in the left-right direction.

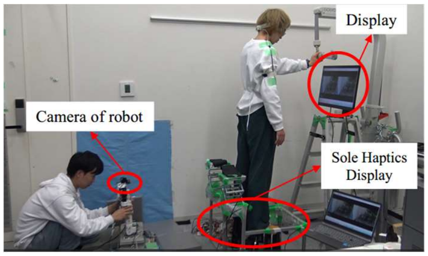


Fig. 8. Operating experiments with whole-body control.

C. Operating Experiments with Disturbances: Impact and Heavy Load

For practical implementation, we conducted an evaluation experiment when disturbances are applied during operating using whole-body joints, as described in case 2 of experiment B. After tuning the sole haptics display, experiments were conducted under the following cases:

- Case 1 (impact): The operator tilted the robot while watching its view on a display, by moving whole-body forward and backward to the maximum angle in an attempt to maintain the robot's balance. During the operation, an impact of approximately 40[N] was continuously applied by repeatedly striking the upper back of the robot with a sponge rod, as shown in Fig. 9.
- Case 2 (heavy load): A heavy load of 5[N] was attached to the tip of an aluminum stick with a length of 250[mm], and each was fixed to both hands of the robot to simulate the act of holding heavy objects. The operator lifted the load while extending their arms to the maximum height and attempted to maintain the robot's balance, as shown in Fig. 10.

Both cases were performed with and without the sole haptics display. Experiment B and C were conducted by three operators.

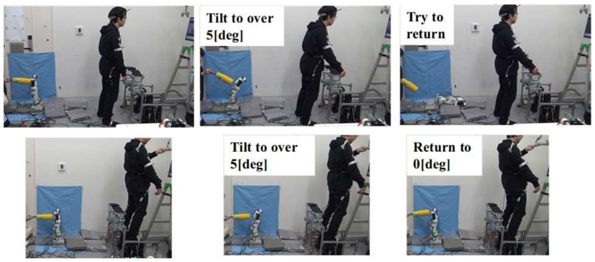


Fig. 9. Whole-body operating experiments with impact. (Above: Vision only. Below: Vision and Sole Haptics.)

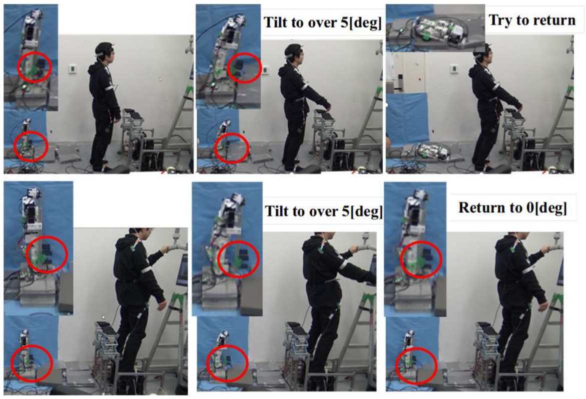


Fig. 10. Whole-body operation experiments with heavy load. (Above: Vision only. Below: Vision and Sole Haptics.)

V. RESULTS AND DISCUSSIONS

We calculated the falling rate from angle data of the robot's body to assess the stability of the robot and evaluated the sense of presence as the percentage of operator's feeling of being a robot indicated by the operators in the survey.

The results of stability and sense of presence under each condition are summarized below for further discussion.

A. Stability

Stability was assessed by the falling rate from angle data of the robot's lower body. Falling rate was calculated as the proportion of falling occurrences and trial occurrences. Since the robot's structural design enables stability within a range of 5[deg] backward to 25[deg] forward, trials over 5[deg] forward were counted as valid trial occurrences. Among these, trials that the robot failed to maintain balance are considered falling occurrences.

Results of stability are summarized under each condition in Fig. 11 with assumptions listed as follows:

i. Fig. 11(a) indicates operating with a single feedback sensation is more stable than both. Sole haptics feedback is more effective at fast speed, while vision feedback is more effective at slow speed. At moderate speed, all feedback conditions show a similar fall rate, which is lowest when both vision and sole haptics are used compared to other speed. Therefore, sole haptics display is considered effective for moderate operation.

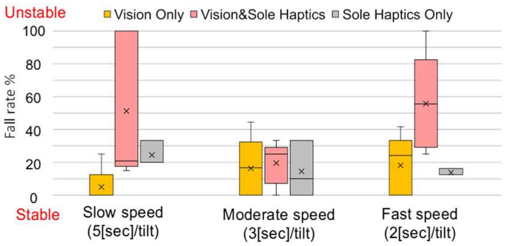
ii. Fig. 11(b) and Table II summarize the results of different feedback sensations in experiment B and experiment C. When operating the whole body without disturbances, feedback of vision only is more stable than that of both vision and sole haptics. However, when disturbances occur, combination of vision and sole haptics is more effective, resulting in a decline rate of more than 56.7% in fall rate compared to vision only. On the other hand, when relying only on vision feedback, the fall rate increases when disturbances are applied compared to the normal condition. In contrast, when sole haptics is shared, the fall rate decreases. This suggests that the effectiveness of sole haptics feedback in operation becomes significant when disturbances are applied.

Reasons are discussed below:

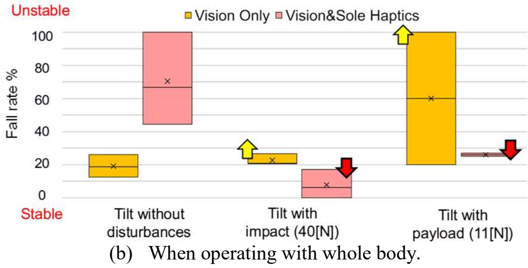
i. When operating with various feedback sensations, timing discrepancy may occur between different sensation, potentially reducing stability. As operating speeds increase, changes in foot sole force become more perceptible. At moderate speed, the timing discrepancy between vision and sole haptics is assumed to be minimal compared to another speed. Also, the balance between the locomotion speed of the linear actuator and the speed at which the operator pushes it back is considered optimal at this speed. Thus, the discrepancy in different speeds may be reduced through appropriate tuning of the force and speed of the sole haptics display, leading to improved timing consistency. Additionally, operator is expected to adjust to the system discrepancies through practice.

ii. The issue of low stability when operating with the whole body lies in the sole haptics display rather than the feedback sensation, including the limited space to move operator's upper body and decreased force to push back the linear actuators while moving the upper body. Therefore, it is considered necessary to reset the experimental environment and to tune the sole haptics display more appropriately.

iii. According to Table II, the pressure on the robot's foot sole increases when disturbances are applied, making it easier to perceive changes in the center of gravity. If the gain and replicated force of sole haptics display are adjusted high when tuning, the operator may perform well at first. However, the operator would become accustomed to the high pressure as their foot sole sensation decreases soon after, making it harder to perceive changes. Therefore, it is necessary to adjust the gain of sole haptics display with real-time monitoring of the operator's sole sensation[16].



(a) When operating with foot.



(b) When operating with whole body.

Fig. 11. Results of stability.

TABLE II. RESULTS OF STABILITY

Condition	Without Disturbances		Impact		Payload	
Feedback sensation	V.O.	V.S.	V.O.	V.S.	V.O.	V.S.
Average fall rate %	19.1	70.4 (-268)	22.7	7.8 (+65.6)	60.0	26.0 (+56.7)
Pressure on big toe of robot N	7.22 (100%)		9.25 (128%)		10.7 (149%)	

※V.O. is the abbreviation for Vision Only; V.S. is the abbreviation for Vision and Sole Haptics. () in the third line shows the reduction in fall rate from V.O. to V.S. () in the fourth line shows the ratio of pressure.

B. *Sense of presence*

The sense of presence was defined as the percentage of the operator's feeling of being a robot indicated by the operators in the questionnaire.

Results of sense of presence are shown in Fig. 12 and Table III with assumptions listed as follows. Since disturbances are objective factors, we summarized the sense of presence of experiment B and C as whole-body operation.

i. Operating with both vision and sole haptics feedback sensations results in a higher sense of presence compared to using a single feedback sensation. When operating with whole body, using vision and sole haptics results in a 21% higher sense of presence on average than using vision only. Also, single feedback of sole haptics provides a higher sense of presence

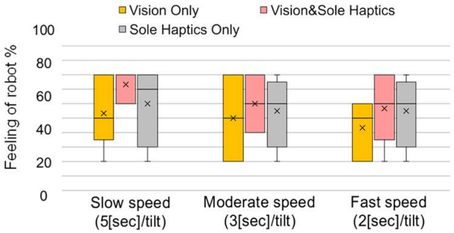


Fig. 12. Results of sense of presence when operating with foot.

TABLE III. RESULTS OF SENSE OF PRESENCE

Condition	Foot			Whole-body	
Feedback sensation	V.O.	V.S.	S.O.	V.O.	V.S.
Average feeling of robot %	50	60	55	64	85

※V.O. is the abbreviation for Vision Only; V.S. is the abbreviation for Vision and Sole Haptics; S.O. is the abbreviation for Sole Haptics Only. All data are conducted under moderate speed.

than that of vision. This verifies that sole haptics feedback is effective to enhance the sense of presence.

ii. Sense of presence is higher when operating at a slow speed compared to another speeds.

iii. Compared to operating with foot only, using whole-body joints for operation generally leads to a higher sense of presence by 25%.

Reasons are discussed below:

i. When operating at fast speed, the inertia of the robot increases, which results in differences between the states of the robot and the operator, potentially causing incompatibility for the operator.

ii. When operating with whole-body control, the response became more human-like, leading to a higher sense of presence. Additionally, compared to sole haptics added from single-foot to both feet and a shifting in the operator's view to robot's view also contributed to enhancing the sense of presence.

When used remotely, network delays can undermine control stability, potentially reducing the operator's sense of presence as the robot's actions may not align with intentions. This discrepancy, especially when combined with vision feedback, may induce motion sickness. Operators are expected to compensate for system delays with improved operating skills, allowing them to predict and adjust for delays. Faster loop cycle can help to minimize delay impacts.

VI. CONCLUSION

In this study, we proposed a method leveraging the operator's inherent sense of stability to operate a bipedal humanoid robot, utilizing feedback from a sole haptics display. We developed an operating system employing bilateral control, which consists of a device replicating sole haptics feedback. According to operating experiments, we confirmed the effectiveness of the developed system. Furthermore, we compared stability and sense of presence in various conditions, including feedback sensations, speeds, and disturbances.

Results demonstrate that sole haptics significantly improves stability and enhances the operator's sense of presence during operation, especially when disturbances occur. Compared to feedback vision-only feedback, both vision and sole haptics feedback reduces fall rates of the robot by over 56% and increases the sense of presence by 21%. It was discussed that to tune gain and replicated force of the sole haptics display and to address timing discrepancy in different sensation feedback is important when operated with the proposed system.

For future research, we aim to enhance operational stability and the sense of presence through the following: First, integrating additional joints and different directions to explore the effects of performing different actions with each foot. Second, developing a control algorithm that adapts to varying sensitivity in foot sole feedback for the linear actuator. Third, increasing the number of participants in future studies to validate effectiveness and investigate individual differences comprehensively. Furthermore, we also aim to devise predictive methods for sole haptics and extend the application of our system to more practical scenarios.

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REFERENCES

[1] K. Darvish *et al.*, "Teleoperation of Humanoid Robots: A Survey," *IEEE Trans. Robot.*, vol. 39, no. 3, pp. 1706–1727, Jun. 2023.

[2] C. Pacchierotti and D. Prattichizzo, "Cutaneous/Tactile Haptic Feedback in Robotic Teleoperation: Motivation, Survey, and Perspectives," in IEEE Transactions on Robotics, vol. 40, pp. 978-998, 2024.

[3] A. Purushottam, C. Xu, Y. Jung, and J. Ramos, "Dynamic Mobile Manipulation via Whole-Body Bilateral Teleoperation of a Wheeled Humanoid," *IEEE Robot. Autom. Lett.*, vol. 9, no. 2, pp. 1214–1221, Feb. 2024.

[4] I. S. Cardenas and J.-H. Kim, "Design of a Semi-Humanoid Telepresence Robot for Plant Disaster Response and Prevention," in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Jan. 2019, pp. 2748–2753.

[5] Ishiguro Y, Makabe T, Nagamatsu Y, et al. Bilateral humanoid teleoperation system using whole-body exoskeleton cockpit TABLIS[J]. IEEE Robotics and Automation Letters, 2020, 5(4): 6419-6426.

[6] N. E. Sian, K. Yokoi, S. Kajita, F. Kanehiro and K. Tanie, "Whole body teleoperation of a humanoid robot - development of a simple master device using joysticks," IEEE/RSJ International Conference on Intelligent Robots and Systems, Lausanne, Switzerland, 2002, pp. 2569-2574 vol.3.

[7] F. Viseux, A. Lemaire, F. Barbier, P. Charpentier, S. Leteneur, and P. Villeneuve, "How can the stimulation of plantar cutaneous receptors improve postural control? Review and clinical commentary," *Neurophysiol. Clin.*, vol. 49, no. 3, pp. 263–268, Jun. 2019.

[8] T. Otani, Y. Kuroiwa, and A. Takanishi, "Plantar Haptic Display to Estimate the Position of the Projected Center of Gravity of a Humanoid," Int. J. Humanoid Robot., p. 2450006, Apr. 2024.

[9] J. Anlauff, J. Fung, and J. R. Cooperstock, "VibeWalk: Foot-based tactons during walking and quiet stance," in *2017 IEEE World Haptics Conference (WHC)*, Jun. 2017, pp. 647–652.

[10] Cikajlo, Imre, Jakob Oblak, and Zlatko Matjačić. "Haptic floor for virtual balance training." 2011 IEEE world haptics conference. IEEE, 2011.

[11] Song, Weibo, et al. "Teleoperation humanoid robot control system based on kinect sensor." 2012 4th international conference on intelligent human-machine systems and cybernetics. Vol. 2. IEEE, 2012.

[12] L. N. M., D. Dajles and F. Siles, "Teleoperation of a Humanoid Robot Using an Optical Motion Capture System," 2018 IEEE International Work Conference on Bioinspired Intelligence (IWOBI), San Carlos, Costa Rica, 2018, pp. 1-8.

[13] P. F. Hokayem and M. W. Spong, "Bilateral teleoperation: An historical survey," *Automatica*, vol. 42, no. 12, pp. 2035–2057, Dec. 2006.

[14] H. Tanaka *et al.*, "Implementation of Bilateral Control System Based on Acceleration Control Using FPGA for Multi-DOF Haptic Endoscopic Surgery Robot," *IEEE Trans. Ind. Electron.*, vol. 56, no. 3, pp. 618–627, Mar. 2009.

[15] Goodrich, Michael A., Jacob W. Crandall, and Emilia Barakova. "Teleoperation and beyond for assistive humanoid robots." Reviews of Human factors and ergonomics 9.1 (2013): 175-226.

[16] S. Morioka and F. Yagi, "Influence of perceptual learning on standing posture balance: repeated training for hardness discrimination of foot sole," *Gait Posture*, vol. 20, no. 1, pp. 36–40, Aug. 2004.