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Design of an Intuitive Master for Improving Teleoperation Task Performance Using the Functional Separation of Actuators: Movement and Gravity Compensation

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Abstract: Teleoperation, in which humans and robots work together to improve work performance, is growing explosively. However, the work performance of teleoperation is not yet excellent. Master–slave systems with different kinematics and workspaces need space-transformation control techniques. These techniques cause psychological fatigue to an operator with poor manipulation skills. In this study, we propose an intuitive master design that focuses on fatigue. Large workspaces reduce mental fatigue; however, they lead to physical fatigue problems. To solve this problem, we reflect the role of actuators in the design, through functional separation using movement and gravity compensation. This study proposes the design and prototype fabrication of an intuitive master K-handler to improve remote-work performance. The K-handler features six degrees of freedom (DoF), an anthropomorphic structure, and a lightweight nature. It has a reach long enough to cover the workspace of the human arm to reduce mental fatigue. In addition, gravity compensation, which can reduce the operator’s physical fatigue during operation, is possible in all workspace areas.

Keywords: teleoperation; telemanipulation; master devices; teleoperation fatigue



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1. Introduction

Teleoperation is defined as an extension of human senses and work capabilities. A system that can expand the operation of a machine or another system from the space where the operator exists to a distant area is called a teleoperation system. This system allows humans to operate robots or mechanical devices from a long distance, as though they are working directly on-site, while securing the operator’s safety [1]. In the late 1940s, Raymond C. Goertz first proposed a mechanical teleoperation system called a master–slave system. Since then, various master–slave remote control systems have been developed by many researchers.

With the robot technology development, not only simple repetitive tasks but also complex and dangerous tasks performed by humans are being performed by robots [2]. However, the current robot technology level does not have the intelligence to allow robots to identify all faults and hazards in the field and act independently [3]. Owing to this intelligence limitation, human judgment is still important, and teleoperation makes this possible.

Unlike typical industrial robots that perform repetitive tasks according to predetermined programs in a static work environment, teleoperation systems can actively cope with changing situations [4]. Therefore, teleoperation is used in various fields, such as, inside nuclear power plants that are difficult to access, space, deep sea, and military areas.

A representative example of a robot’s inability to perform tasks autonomously is a disaster situation. The disaster-response work environment is a typical external environment

without any operational pattern. Currently, most disaster-response systems depend on the workforce and construction equipment. This is a dangerous environment where secondary accidents, such as fires, occur. For this reason, research on robots that can work on behalf of humans in a disaster-prone environment is being conducted to protect workers from danger. However, in an unstructured environment, high-level work requires a high level of judgment intelligence for executively reacting to different situations; therefore telemanipulation is used because robots cannot perform any executive decisions independently.

The expectations for telemanipulation task performance are increasing owing to the expansion in the teleoperation market. In the past, most of the attention was focused on how slave robots would perform their tasks. The possibility of a teleoperation mission depends primarily on whether or not the slave robot can handle the task. Recently, research was conducted on master devices to improve maneuverability, control systems for realizing a sense of telepresence, and slave robots' ability [5,6]. The critical point when applying teleoperation to various fields is not only the task capacity but also how to perform the mission effectively. Thus, the improvement of human–robot interaction (HRI), which is the operability of the master arm, is essential [7].

Methods of remotely controlling the target robot include directly manipulating each joint, such as with a joystick or lever, and using the kinematics of the robot, such as those of a master–slave system. Joysticks and levers are one of the easy ways to configure a teleoperation system, allowing simple operation [8]. However, there is a limit to performing complex joint movements or controlling slave robots with high DoF. This counter-intuitive manipulation method makes the operator feel a psychological burden, and training time is required to become used to it [9,10]. The master was developed in the form of a manipulator to solve this problem. These masters have a replica type that imitates a slave and a universal type that can be used for a general purpose.

Research on improving the master's maneuverability to improve teleoperation task performance is actively underway. Recently, universal-type masters with dissimilar kinematics to those of slaves were mainly developed in multi DoF systems owing to the disadvantages of replica-type masters in terms of production and cost. Various types of commercial devices have also been released and used in many studies. However, although commercial devices are mainly desktop-sized and have low force and workspace capabilities, they have the advantage of being universally applicable to various slaves [11–14].

In addition, masters with a large workspace, in wearable robots used for specific applications, were also studied. These masters incorporate space relocation technologies or continuing hardware improvements to overcome their respective physical limitations to improve operability [15]. Locking a valve or screwing walls using tools is a straightforward task for humans. However, the teleoperation system takes a long time to perform tasks using conventional methods. Moreover, the master maneuverability to improve teleoperation task performance is still a challenge.

Our previous research investigated the teleoperation of special-purpose machinery with 14 DoF of a dual-arm mechanism for disaster response as illustrated in Figure 1 [16]. This heavy machinery can be easily and efficiently operated by unprofessional firefighters, compared to excavators, which were difficult to operate in a disaster environment. Therefore, the machinery was designed to perform complex and diverse tasks as a dual-arm type. The machinery required an intuitive master capable of force-reflection bilateral remote control for dual-arm collaboration.

Commercial master devices are challenging to employ in our applications because of the workspace or force capability limitations. Therefore, we proceeded with the study of the design of intuitive masters. In this study, we present the design direction of the intuitive master device using the functional separation of actuators and introduce the master that anyone can easily implement and produce inexpensively. The master is called a K-handler, which features six DoF, lightweight, and a large workspace, and is capable of haptic operations, force-reflection control, and gravity compensation as illustrated in Figure 2.



Figure 1. The dual-arm manipulator for special-purpose disaster-response machinery from KITECH.

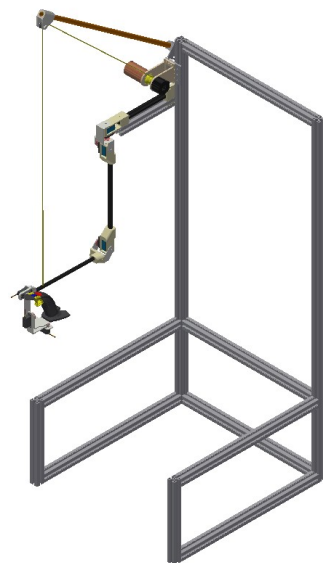


Figure 2. The prototype 3D model of K-handler.

This paper is organized as follows: Section 2 discusses the need for intuitive masters. Specifically, the characteristics that a master should have are explained. Section 3 identifies the design requirements and presents design directions. Section 4 introduces the K-handler prototype and control architecture. Section 5 verifies the K-handler experimental results on workspace, gravity compensation, and teleoperation task performance. Section 6 is the conclusion of this paper.

2. Physical and Mental Factors to Hinder Intuitive Teleoperation

Various studies are being conducted to improve the task performance of teleoperation. However, it is difficult to expect a major improvement in task performance by simply applying the teleoperation technology to robot systems.

The task performance of teleoperation can be upgraded through an integrated improvement of all the master, slave, and control systems constituting teleoperation. Slave ma-

nipulators, which perform tasks in the field to improve teleoperation task performance, are being developed to be more powerful and capable of performing more diverse tasks, as with industrial robots. There are also many studies on control techniques to offset the difference in RoM from the dissimilar kinematics structures of the master and slave, or the sense of reality to convey more field information to the operator. Furthermore, we would like to study the master design to improve the task performance of teleoperation.

Teleoperation is when robots perform tasks on behalf of workers. Naturally, it is a human-in-the-loop system that requires frequent operator intervention, because it is difficult for robots to handle tasks autonomously. Therefore, interest in the convenience and operability of master devices began to grow, and many researchers have conducted research on intuitive masters.

In previous studies, the structure of the master tended to depend on the slave or the slave's mission. In the beginning, replica-type masters were used to easily and efficiently control the slaves. The replica-type master is a simple way of controlling the slave as it appears. Using the replica-type master, the operator can manipulate the master–slave pose without their forward and inverse kinematics calculations. This method does not require complex control techniques, such as coordinate system transformation. However, as described above, the replica-type master is not advantageous in terms of control and cost, as it is developed in a complex structure with the multi DoF of the slave robot.

Recently, several universal masters that can be applied to multiple applications have been commercialized. Universal masters avoid complex structures and adopt task space control rather than joint space control to be applied to various slave robots with different mechanical designs, increasing usability and user friendliness. These devices are versatile; however, most of them are desktop-sized, with limited workspace and low force capacity. Other researchers tried to modify and combine these commercial devices or use coordinate system transformation, such as workspace mapping, to overcome physical limitations [17].

2.1. Intuitiveness in Master Devices

The word intuitive means to directly grasp an object impulsively. It can be said that, it is intuitive for a person to use a familiar manipulation method. Humans have always lived by moving their arms freely in the task space. For example, humans do not move while thinking about the angle between the elbow and shoulder to reach the object; instead, they move instinctively. In other words, humans do not move their arms through complicated calculations. We believe that the intuitiveness of manipulation in the master's design is a significant factor in improving the task performance. Therefore, we would like to use the word “intuitive” in the design of the master to imply that ‘as if a person naturally moves their arm’. If the operator can manipulate the master as if their arms were moving, the psychological burden could be significantly reduced.

2.2. Problems of Counter-Intuitive Operating Methods

Take excavators as an example of the problem of counter-intuitive control methods. The operator controls the speed of each joint using several levers or joysticks corresponding to each joint of the excavator. To operate an excavator consisting of rotating joints in combination with two or more joints, such as linear motion, the excavator is controlled using a combination of two or more levers, and takes considerable training time to become an expert [18]. Naturally, task performance is dependent on the operator's proficiency. Even a skilled operator may experience a psychological load and make mistakes in long-term use [10].

People feel stressed when the control method is unfamiliar or they cannot operate the object properly, such as when driving a car for the first time. A psychological load is felt when a calculation process for spatial transformation or discontinuity is required. People may feel scared when they are new to manipulation or burdened from a mission failure. This counter-intuitive manipulation accumulates mental fatigue, such as stress, mental load, and fear, which will result in less time for performing tasks and more mistakes.

As illustrated in Equation (1), mental fatigue can be expressed as a cumulative sum of stress, mental load, fear, etc.

$$\text{mental fatigues} = \int (\text{stress} + \text{mental load} + \text{fear} + \dots) dt \quad (1)$$

2.3. Fatigue in Teleoperation

During telemanipulation, operators experience a mental load because of differences in handling methods, and they also experience physical fatigue from working with their arms raised [19]. We ensured that the master is intuitive for as long as task-space control is possible, and we looked at the master from the workspace-size perspective by focusing on the commercial desktop masters. Desktop masters with relatively small workspaces use some conversion techniques to control bigger slaves, which causes mental transformation and discontinuity, resulting in mental fatigue. However, having an extensive reach widens the work area, making it easier for physical fatigue to occur.

- **Physical Fatigue**

Physical fatigue refers to a sense of incompetence that occurs in the muscles. In teleoperation, physical fatigue is tiredness that results when the operator manipulates a master. The operator mainly manipulates the master device using their hands, with their arms extended or raised. At this time, if the master robot cannot sufficiently compensate for the gravity generated by its weight, the operator becomes tired easily. In addition, the master's frictional force, inertia, and interference act as a load on the operator. Fatigue accumulates when the master is used continuously, for a long time, by the operator. Physical fatigue is often problematic, and it increases with increasing workspace.

- **Mental Transformation**

A teleoperation system using a replica-type master of the same structure and size as the slave does not require a coordinate system transformation. However, as mentioned above, the replica-type master is not efficient; therefore, the commonly available universal-type master is used. Universal masters have a different structure from that of the slave; therefore, the RoM of each joint and size of the reachable workspace are different. The position or force dimension differs between the operator's arms, masters, and slaves, and the operator must mentally convert the position and direction of the force to match them. In addition, the difference in the workspace requires control techniques, such as mapping and spanning [20]. These control techniques cause transformation and distortion of the coordinate system, making the operator always consider and manipulate the mental transformation [21].

- **Discontinuity**

Discontinuity refers to a movement, such as that of lifting off the computer mouse when it can no longer move at the edges of the mouse pad. When there is a limited master workspace for the operator, clutch action is needed to temporarily block and reconnect the connection of the position and force between the master and slave. When the clutch motion occurs, the position or force must be calculated relative to the previous position in a three-dimensional space, causing mental fatigue. Different workspaces in the master-to-slave operation result in discontinuity. The clutch system may be necessary because the master's workspace is relatively smaller than the slave's in teleoperation. However, from the mental fatigue perspective, minimizing the number of times of this discontinuity is a way of lowering the cognitive load. A large master's workspace can reduce the number of discontinuities.

3. Design of K-Handler

We believe that intuitive masters should minimize mental fatigue as well as mental transformation and discontinuity. In other words, this master should be task-space controllable and have a large workspace. As humans can freely manage their arms from long

empirical trial-and-error techniques, if operators can give commands to the master devices naturally as if they move their arms, it can reduce mental fatigue and improve teleoperation task performance. However, physical fatigue is also one of the problems that need to be solved. A good master must minimize interference with the operator, friction, and inertia and requires gravity compensation. The master we would like to propose is an intuitive master that even beginners can operate for a long time without any operational difficulties.

In the robot arm design, there is always a trade-off relationship with other variables, such as link length, actuator selection, inertia, RoM, etc. [22,23]. As mentioned above, intuitive masters should be designed to minimize mental fatigue. Furthermore, it was explained that designing a larger master's workspace can increase intuitiveness. However, if the link length is designed to increase the master's workspace, the actuators require a huge force, increasing the frictional force and inertia.

Eventually, the system size increases, RoM becomes limited, control response decreases, and cost increases. We set some design requirements that the master must satisfy to solve these problems, and we solved the contradictions derived from them using the functional separation and applied them to the design. The following are the design requirements of an intuitive master to increase teleoperation task performance.

The intuitive masters

1. Should have a large workspace.
2. Should be able to reduce physical fatigue.
3. Should not interfere with the operator's movement.
4. Should be free from collision with the operator [24].
5. Should be capable of bilateral teleoperation.

To reduce mental transformation or discontinuous sections that cause mental fatigue, a larger workspace is required. Having a large workspace will lead to a gravity compensation problem. The gravity compensation system is needed to reduce physical fatigue when the master is used for a long time or with outstretched arms. To improve operability, the master must move smoothly to not interfere with the operator's movement. To achieve that, friction, inertia, vibration, clearance, etc., of the master devices must be minimized, and the actuator must be backdrivable.

The master that interacts at the closest distance to operators should not make any collision, even if it is for safety. In addition, when operators and masters share a workspace, collisions create shaded areas of the workspace and damage the intuitiveness of manipulation. Finally, to improve the task performance of teleoperation, bilateral teleoperation must be possible, and a system that implements telepresence, such as haptic-, guiding-, and earthing systems, is needed [25,26].

It is not easy to satisfy all design requirements of the intuitive master described above. The relationship between each design requirement and design variable was analyzed as shown in Table 1. Considering this table, there is a contradiction in the selection of actuators. In manipulating a giant slave, the larger the master's workspace, the more intuitive it is and the less mental fatigue it can cause. Under this condition, we select the variable α , as shown in Equation (2), as a value representing the ratio of the human arm's workspace to the master's workspace. If α is approximately equal to or greater than one, the master can cover the workspace of the human arm, which boosts intuitive manipulation.

$$\alpha = \frac{(\text{workspace of master})}{(\text{workspace of human arm})} \quad (2)$$

The link length is extended to enlarge the master's workspace, and a more powerful joint actuator is required. Similarly, to implement the gravity compensation function to reduce physical fatigue, it is necessary to use actuators with a high reduction gear ratio or high power. However, from design requirement No. 3, an actuator with a low reduction gear ratio should be used. Moreover, an actuator that exerts a large force may be restricted to a slim design.

Table 1. Design table of K-handler requirements.

	1	2	3	4	5
size	$\alpha \geq 1$ ¹	-	-	The greater the better.	-
DoF	6 or more	-	-	Redundancy	Redundancy
Actuator	High power to weight ratio	$g(\theta)$ ²	Low friction, low inertia, backdrivability, low vibration	Slim design	Force reflection and capability

¹ α is workspace ratio from Equation (2). ² Gravity compensational force.

The contradiction that occurred in this way was applied to the design of the master device by separating the motion and gravity compensation functions among the roles of the joint actuator, using the separation law of the TRIZ. The joint actuator only controls movement and does not require much force. In addition, if a separate gravity compensation device driven by wires is directly connected to the wrist, it can implement the gravity compensation function while having a large workspace, and it can be designed to have slim and low inertia.

The functional separation of the joint actuator in movement and gravity compensation described above is more efficient than otherwise. Using the two-link planar manipulator as an example, as illustrated in Figure 3, the maximum torque required for the gravity compensation of the robotic arm of a conventional serial mechanism is the sum of the gravity compensation torque lMg and movement torque τ_{movement} , as shown in Equation (3).

$$\tau_{1,\text{max}} = lMg + \tau_{\text{movement}} \quad (3)$$

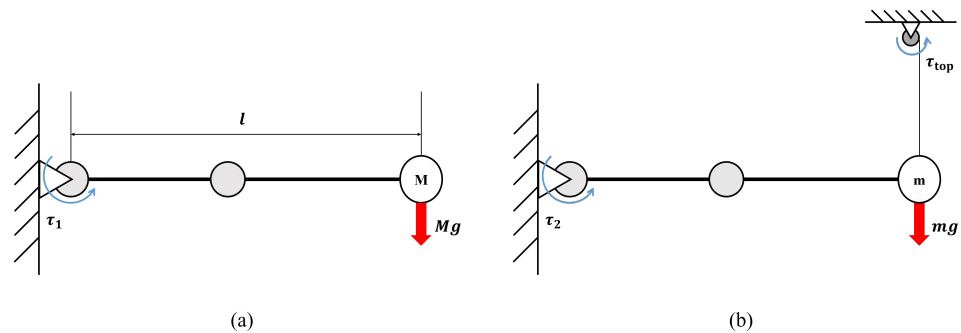


Figure 3. Comparison of the maximum gravity compensation torque at and (a) 2 DoF planar manipulator and (b) 2 DoF planar manipulator with a wire-driven direct-gravity compensation system.

The link's weight and the actuator were ignored. Conversely, if the wire is directly connected to the end where the load is concentrated to compensate for gravitational force, the maximum torque is rMg , where r is the radius of the pulley.

$$\begin{aligned} \tau_{2,\text{max}} &= \tau_{\text{movement}} \\ \tau_{\text{top,max}} &= rMg \end{aligned} \quad (4)$$

The gravity compensation torque is eliminated in the joint, and only the movement torque τ_{movement} remains as shown in Equation (4). In general, l is approximately 70 cm long, assuming that it is a human arm length, and the radius of the top pulley is set to 2 cm, which is approximately 35 times different and is also efficient in terms of energy.

However, when the wrist is out of the center of the fixed top pulley, a restoring force acts toward the central axis of the pulley as illustrated in Figure 4. This restoring force is a function of the angle θ formed by the upper pulley's central axis and the wire; θ is an acute

angle, and $Mg\sin\theta$ is significantly small compared to Mg . This value is simply applied to the controller by using Equation (5).

$$\tau_\theta = J^T M \vec{g} \sin\theta \quad (5)$$

where τ_θ denotes each joint torque and J denotes jacobian matrix. This is the result of ignoring the weight of each joint actuator and the link weight, and if the weight is reflected, there will be a more significant difference. The sum of forces that joints actuators must exert is $Mg\sin\theta$, smaller than Mg in a typical way. The force required for the wire to achieve gravitational equilibrium is $Mg\cos\theta$. The wire system allows direct compensation to the wrist, reducing the link length effect, and making it efficient in a serial structure. Thus, applying a gravity compensation system by straightening the wire to the wrist through separating the function of the actuator into movement and gravity compensation, allows the master covering the human workspace to be articulated with small, low-power actuators.

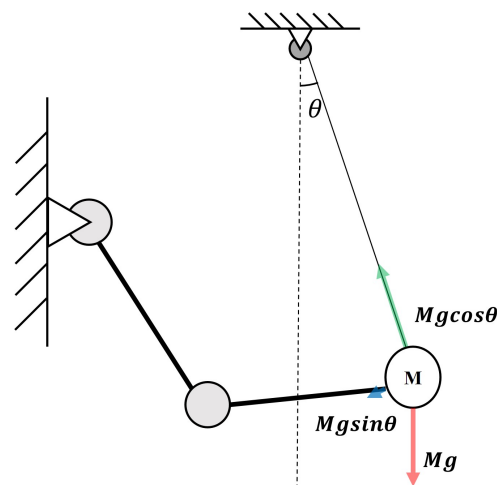


Figure 4. The restoring force that occurs when the end-effector is out of the pulley's center axis.

4. Implementation of K-Handler

4.1. Prototype

Based on the design requirements and parameters described in the previous chapter, a six DoF prototype was realized. As illustrated in Figure 5, the K-handler consists of three upper joints responsible for translation and three lower joints accountable for the orientation of the wrist. The wire-driven gravity compensation device located at the top is directly connected to the wrist of the K-handler through a pulley. The coordinate system and RoM of each joint are listed in Figure 6 and Table 2. The upper DoF are made up of serial mechanisms. The rotational axes of the lower joints intersect at one point and are orthogonal to each other as shown in Figure 7. This means that the translation and orientation of the wrist are physically separated. The K-handler structure is similar to a human arm, providing an intuitive movement to the operator.

The K-handler consisted of six joints, including a small low-power DC motor, position sensor, and current sensing resistor, and its links were made of carbon pipes to reduce the weight. The joints were constructed using a 1.42 Nm DC motor for the three upper joints and a 0.25 Nm DC motor for the three wrist joints. The controllers are embedded inside the motor using an STM32F0 series small MCU. Each controller transmits and receives information on the position, current, and motor output at a speed of 1 Mbps using an RS485 communication. The end-effector is a modified handle of a Logitech commercial joystick. There are 10 pushbutton switches that provide functions, such as grasping, variable changing, and mode changing.

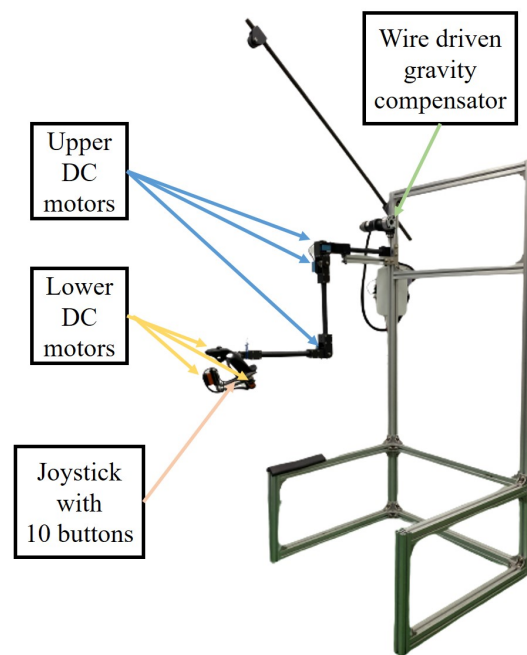


Figure 5. The prototype of the K-handler.

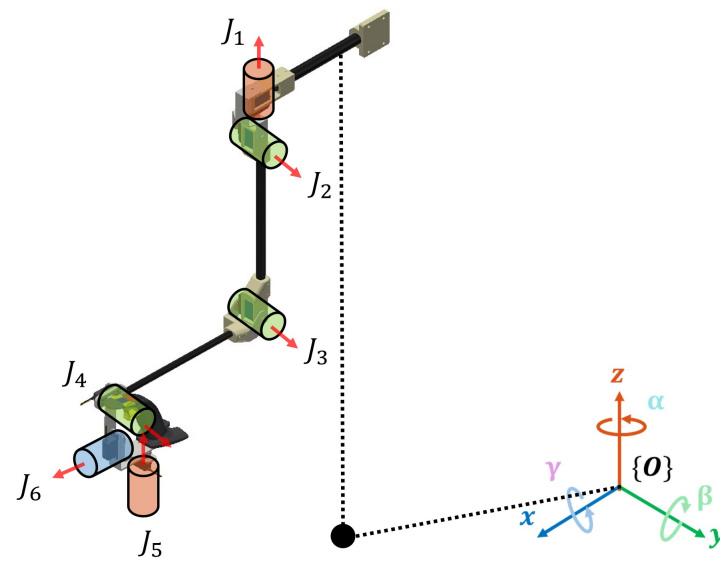


Figure 6. The coordinate system of the K-handler.

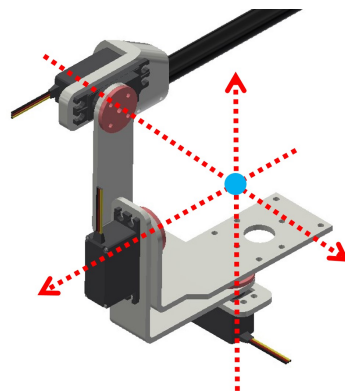


Figure 7. The wrist orientations intersect at one point.

Table 2. Specification of K-handler.

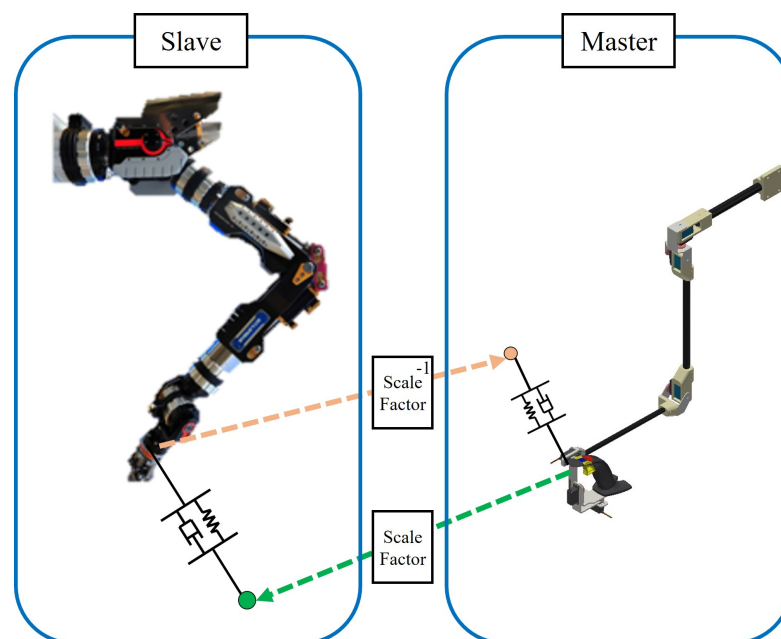
Joint	RoM [°]	Length of the Link [m]	Axis
J ₁	$-120 \leq \theta_1 \leq 50$	0.04	Yaw
J ₂	$-90 \leq \theta_2 \leq 80$	0.352	Pitch
J ₃	$-170 \leq \theta_3 \leq 0$	0.354	Pitch
J ₄	$-70 \leq \theta_4 \leq 70$	-	Pitch
J ₅	$-70 \leq \theta_5 \leq 70$	-	Yaw
J ₆	$-70 \leq \theta_6 \leq 70$	-	Roll

4.2. Control Architecture for Teleoperation

The K-handler is a master device designed to improve intuitiveness. The force reflection for telepresence is essential in teleoperation. The bilateral teleoperation system as shown in Figure 8 was implemented and tested in this study. The controller is implemented based on the Cartesian-space PD controller. It is a virtual spring and damper system (VSD) between the desired position and the current position. The position and velocity of the slave are converted to a motion information on the master coordinate system through a scale factor to become a desired position, and the current position and velocity error with the master generates $F_{vsd} \in \mathbb{R}^3$. The proposed VSD controller is derived as follows:

$$F_{vsd} = k_{pm}(X_{s,m} - X_m) + k_{dm}(\dot{X}_{s,m} - \dot{X}_m) \quad (6)$$

where $k_{pm} \in \mathbb{R}^3$ is a virtual spring coefficient, and $k_{dm} \in \mathbb{R}^3$ is a damping coefficient acting on the master; $X_{s,m} \in \mathbb{R}^3$ is position of the slave converted to the coordinate system of the master; $X_m \in \mathbb{R}^3$ is position of the master.

**Figure 8.** The bilateral teleoperation concept of K-handler.

This VSD system allows the operator to feel the force of resistance through the master when the slave robot is unable to move due to an obstacle or when there is a speed difference between the master and the slave.

Here, the overall K-handler control architecture is shown in Figure 9. The K-handler is capable of bilateral teleoperation and transmits haptic force $F_{haptic} \in \mathbb{R}^3$ in direction of translation to the operator using the motion information of the slave. Master–slave systems with different kinematics are converted to each other’s coordinate systems through

scale factors. The positional difference on the master coordinate system creates the virtual force F_{vsd} , which is converted into joint torque.

In wrist orientation case, $F_{restoring}$ and F_{wire} become zero. It is also possible to calculate the gravity compensation torque of the wire device through the position of the master itself. The τ_{top} and τ_{θ} mentioned in Equations (4) and (5) in the previous chapter can be obtained using the motion information of the K-handler. Through K-handler's forward kinematics, the position of the wrist can be calculated to obtain theta, which is the angle between the wrist and the central axis of the fixed pulley. Then,

$$\begin{aligned} F_{restoring} &= M \vec{g} \sin\theta \\ F_{wire} &= Mg \cos\theta \end{aligned} \quad (7)$$

where $F_{restoring} \in \mathbb{R}^3$ and F_{wire} is scalar because the wire that has passed through the pulley is not directional. The $F_{restoring}$ and F_{wire} give the static force required for K-handler gravity compensation. This $F_{restoring}$ is multiplied by the master's Jacobian transpose matrix to calculate joints torque and acts as an input to the joint through motor drivers.

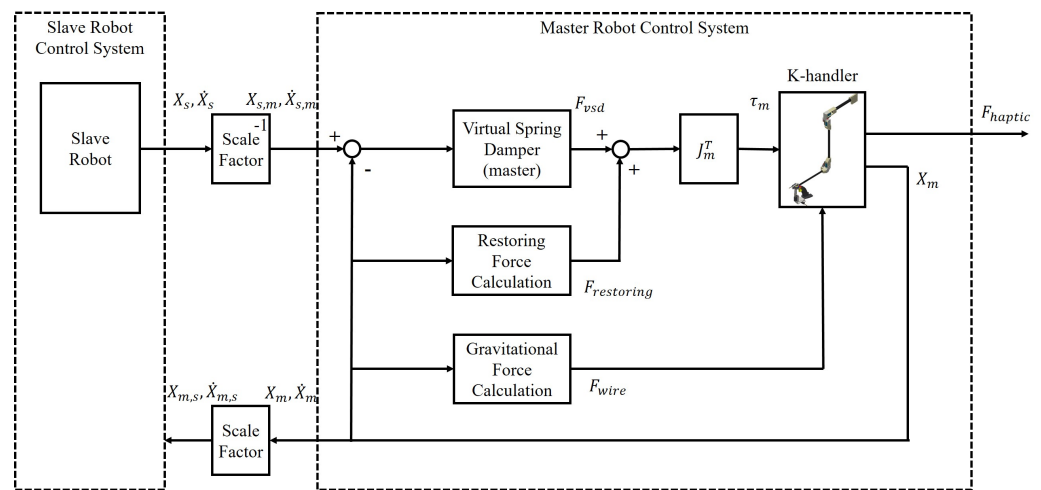


Figure 9. The control architecture of the K-handler.

5. Verification of K-Handler

Three methods were verified to evaluate the intuitiveness and performance of the K-handler. First, we argued that the intuitive master in telemanipulation should be large enough to cover the human arm workspace, and we confirmed the size of the proposed K-handler's workspace. Second, most masters with large workspaces have problems with gravitational compensation, which makes the system heavy and bulky. We tested whether our proposed wire-driven gravitation compensation device acting directly on the wrist with a large workspace can solve this problem at the same time. Third, to verify the K-handler's teleoperation task performance, the teleoperation experiment was conducted to draw along the prepared circle via slave robot seven-DoF hydraulic manipulator UW. Ten subjects were experimented with to secure objectivity, and statistical analysis of the teleoperation task performance was conducted.

5.1. Workspace Analysis

Figure 10 illustrates the workspace of the K-handler for the right arm. A human model is projected for comparison with the human right arm workspace. As described above, the K-handler can cover the workspace of the human arm to reduce mental fatigue during remote work. The orientation of the wrist may operate as much as RoM within the workspace.

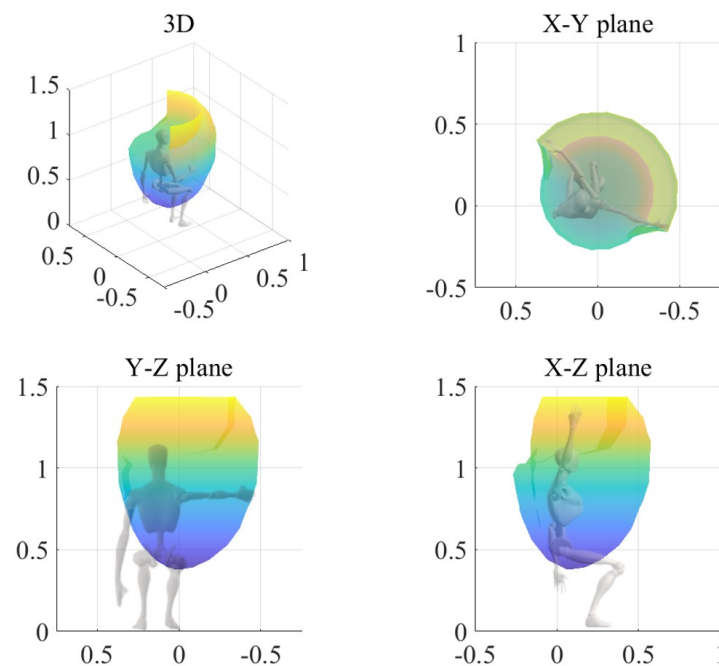


Figure 10. The workspace analysis of the K-handler.

5.2. Gravity Compensation Validation

Figure 11 depicts the gravity compensation experiment. If most of the force against gravity is directly compensated through wires attached to the wrist, each joint only needs to be involved in the restoring force. In this experiment, the mass is 0.4 kg of the measured wrist part, and the angle θ can be calculated from K-handler's forward kinematics. Since the angle θ is an acute angle, it is confirmed that this restoring force is significantly smaller than the Mg of the conventional method, and the forces calculated in Equation (7) was input to K-handler. Since this experiment is not a teleoperation test, the external force F_{vsd} produced by the slave position is zero, then compliance motion is possible. In order to find out K-handler's ability to compensate for gravitational force of its weight, an experiment was conducted to release hand at negative and positive positions in the X, Y, and Z directions during free motion. The K-handler confirmed that gravity compensation is possible in all workspace areas.

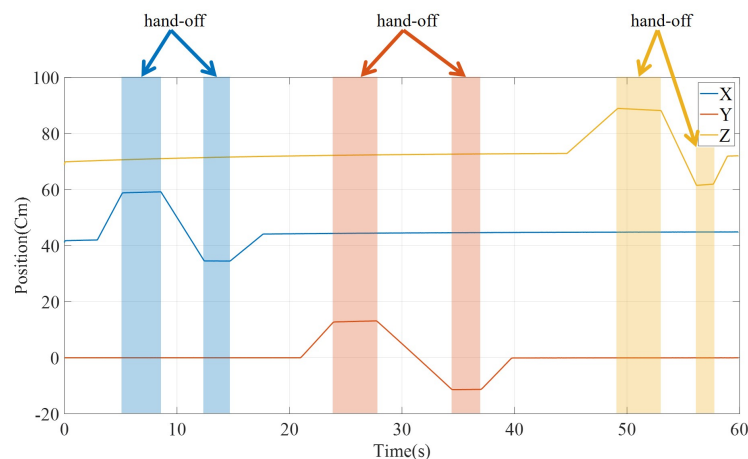


Figure 11. The end-effector position of K-handler to verify the gravity compensation performance.

5.3. Teleoperation Task Performance

This section presents the experimental results obtained for teleoperation task performances. The experimental setup, see Figure 12, consists of the K-handler and the 7DOF slave manipulator UW. The UW is a hydraulic manipulator with a maximum reach of 1.7 m and consists of a combination of linear and rotary actuators. The actuators are operated by servo valves. The control period of the master and slave is 4 ms and the pressure supplied to the UW is 140 bar. To overcome the difference in the workspace, the scale factor of the master for the slave is $\{2, 2, 2\}$, which is doubled in each axial direction.

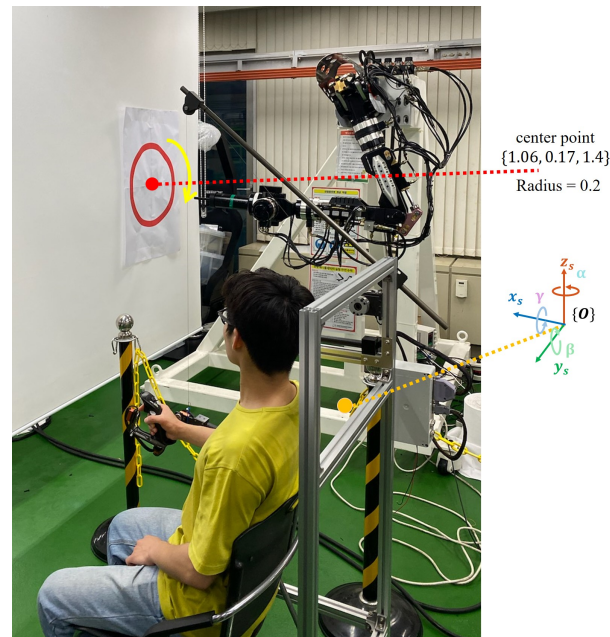


Figure 12. Teleoperation task performance experiments.

This experiment performed ten turns clockwise to draw a circle with a radius of 0.2 m attached to a soft wall to verify the teleoperation task performance of the K-handler. To prove the intuitiveness of the K-handler, the experiment was conducted on a person who first encountered K-handler. In addition, in order to examine the effect of the gravity compensation function on the teleoperation task performance, $F_{restoring}$ and F_{wire} were excluded from Figure 9, and further experiments were conducted and compared.

Figures 13 and 14 show the position in 3D during ten turns of each experiment. The statistical analysis of position for comparing the teleoperation task performance in each experiment are shown in Figures 15 and 16. Above all, even beginners could operate the system, and significant results could be confirmed depending on the presence or absence of a gravity compensation.

Figure 15 shows the distance of the end pointer from the center point of the circle. Figure 16 illustrates the depth to determine how far the end pointer deviates in the X-axis direction. When the master device relieves the force caused by gravity, it can be seen that more precise movement is possible and provides stability. In the experiments, the case with the gravitational compensation of the K-handler showed excellent results in the mean and deviation.

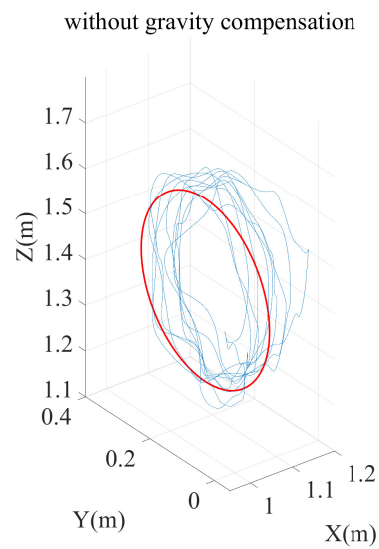


Figure 13. End-point trajectory of the UW during experiments in 3D without gravity compensation of K-handler.

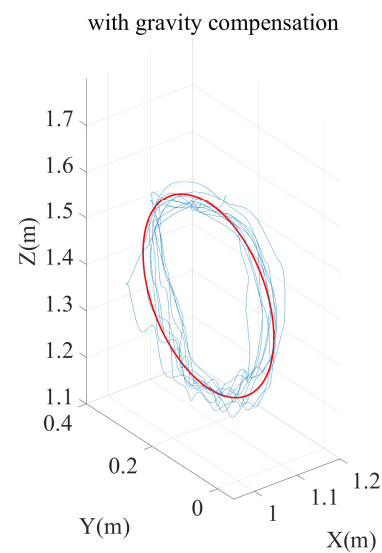


Figure 14. End-point trajectory of the UW during experiments in 3D with gravity compensation of K-handler.

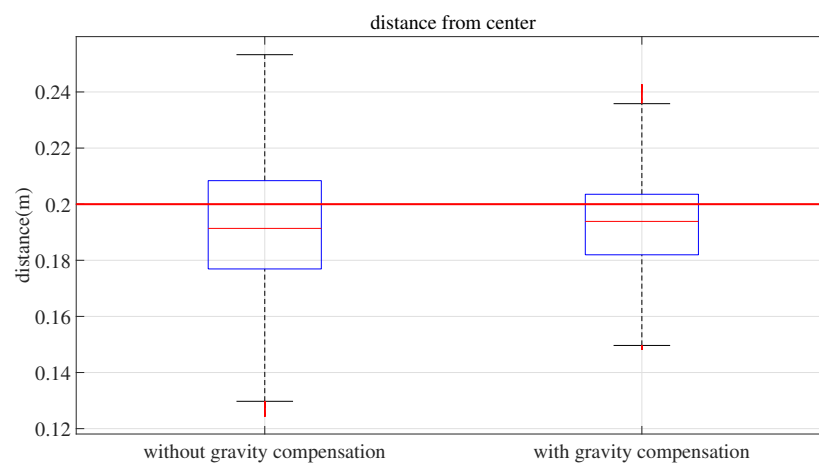


Figure 15. The mean and deviation for the distance from center.

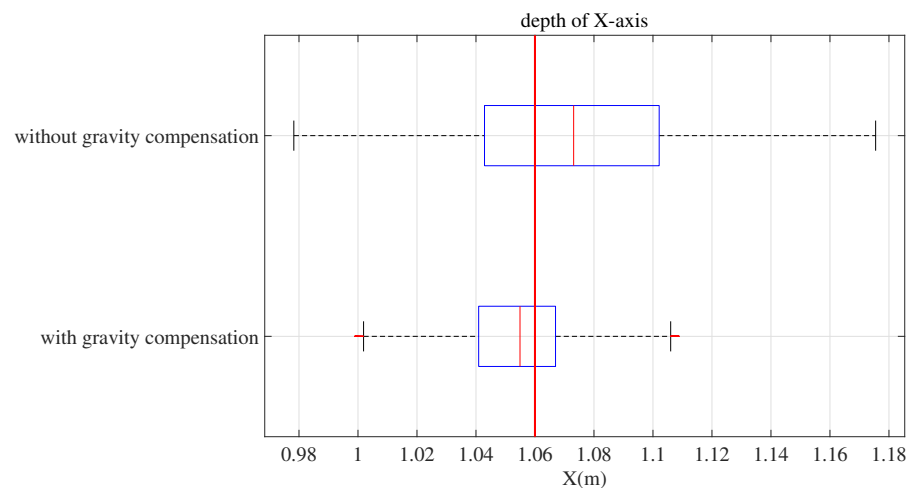


Figure 16. The mean and deviation for depth in the x-axis.

Based on the previous experiment, we expanded the experimental group to 10 subjects to secure more objectivity. The experiment was repeated, and a NASA task load index (TLX) survey was conducted at the end of each experiment. To prevent the subjects' proficiency in the behavior of K-handler and UW from affecting the experiment, the order of gravity compensation functions was randomly conducted for each subject. Figures 17–20 show statistical results for the experiments of 10 subjects. Statistically, it is not possible to show a quantitative degree of improvement by comparing only the average value. However, referring to Figures 17–20, it can be said that the distribution of the UW end-effector positions is more accurate and stable when gravity compensation function is activated.

The NASA TLX survey was used to measure the load of teleoperation experiments. The results for the NASA TLX scores from the subjects are shown in Figure 21. After the experiment was conducted on six items, the experimenters scored between 0 and 100 based on their own criteria. The higher the score, the more difficult it is to perform the task. Although the subjects were new to the master–slave system using K-handler, we confirmed that the task load was significantly reduced in all items when there was a gravity compensation.

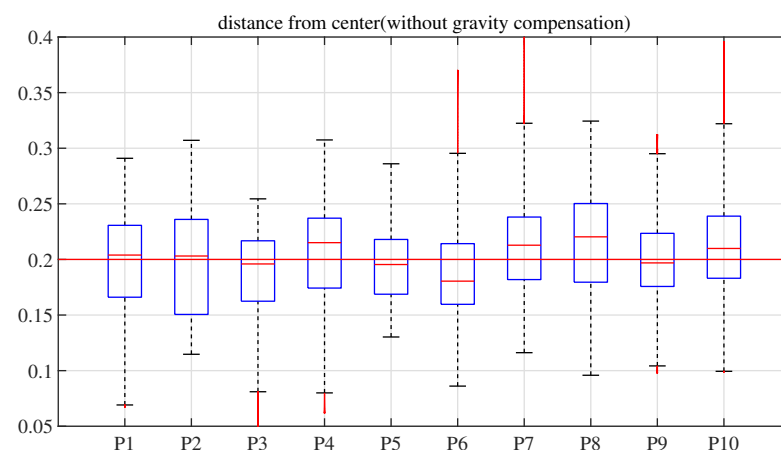


Figure 17. Distribution of the UW end-effector distance from the center of 10 subjects without gravity compensation of K-handler.

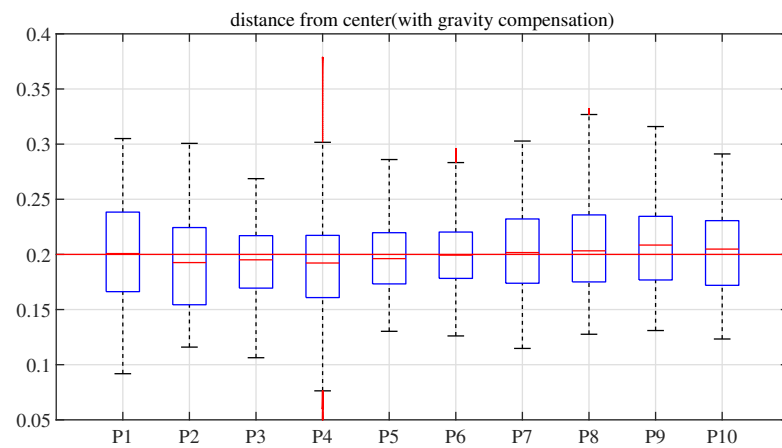


Figure 18. Distribution of the UW end-effector distance from the center of 10 subjects with gravity compensation of K-handler.

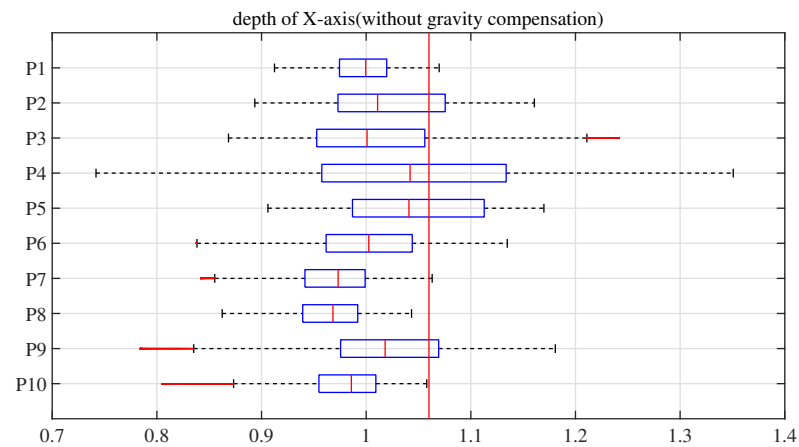


Figure 19. Distribution of the UW end-effector depth in x-axis of 10 subjects without gravity compensation of K-handler.

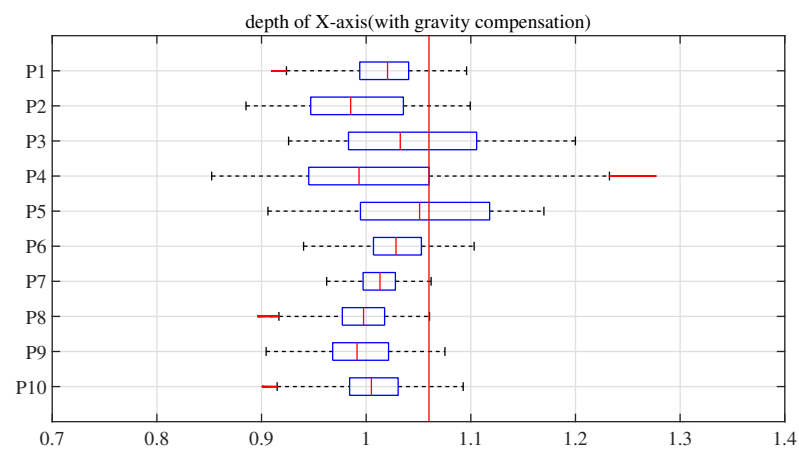


Figure 20. Distribution of the UW end-effector depth in x-axis of 10 subjects with gravity compensation of K-handler.

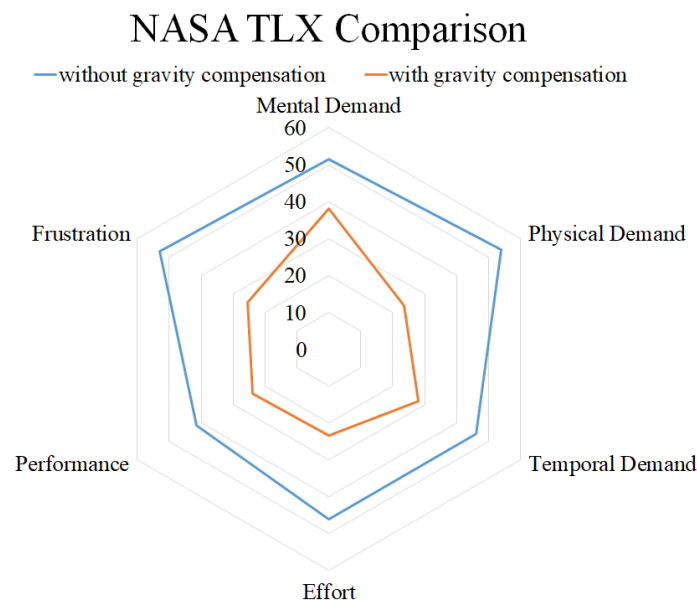


Figure 21. NASA TLX score comparison.

6. Conclusions

In this study, the design direction of the intuitive master device was presented, and the prototype K-handler was proposed. An intuitive master requires a large workplace to reduce mental fatigue. However, most master devices with long reach cause physical fatigue to the operator. Consequently, we designed a K-handler from the fatigue perspective. The functional separation of the actuators reduced the power required for the gravity compensation of the anthropomorphic workspace master. The joints could be constructed using small, low-power actuators. The K-handler is an exoskeleton type; however, it is not a wearable robot.

Moreover, there are no binding devices. Therefore, it is possible to ensure the operator's safety from malfunctioning joint actuators. The K-handler requires an additional actuator to drive the wire for gravity compensation; however, the overall required torque is significantly reduced, which increases the overall efficiency. The K-handler is characterized by a lightweight and low inertia. Moreover, it has a reach long enough to cover the workspace of the human arm so that it can cover most of the operator's arm and reduce the mental burden. In addition, gravity compensation is possible in all areas of the workspace, thereby, reducing the operator's physical fatigue during teleoperation.

We confirmed the convenience of the K-handler and its potential in teleoperation applications. Through teleoperation task experiments, we confirmed that even untrained beginners could perform the task. In addition, we verified that the gravity compensation relieved the physical fatigue of the operator and allows them to manipulate the K-handler with smaller efforts. The NASA TLX scores confirmed that the gravity compensation feature reduces the work load.

Overall, the K-handler is an intuitive master device with a large workspace and can improve remote work performance with gravity compensation ability. Our research will expand into the extension of dual arms, application of special-purpose machinery, and interpretation of redundancy in future works. Furthermore, we would like to check the excellence of qualitative K-handler through a survey by dealing with various experimental groups.

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J.C.; visualization: S.U.C., J.K. (Jungyeong Kim) and J.S.; supervision: J.C.; project administration: J.C.; funding acquisition: J.C. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

K-handler	Kitech-handler
DoF	Degree-of-Freedom
RoM	Range of Motion
HRI	Human–Robot Interaction
VSD	Virtual Spring-Damper system

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