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Posture Operating Method by Foot Posture Change and Characteristics of Foot Motion

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ABSTRACT The lower limbs of the human body actually can perform the multiple-degree-of-freedom motion, just like the upper limbs. This suggests the possibility for the lower limbs to be used in the operation of multiple-degree-of-freedom devices, such as a robot arm. With that point in mind, the present paper focuses on the foot motion and examines its characteristics under the situation in which the posture of the object is manipulated by the posture change of the foot. First, we investigated how well the foot of the operator moved in accordance with the intention of the operator in order to clarify the motion characteristics of the foot experimentally by measuring the foot motion with a motion capture system under the assumption that the operator manipulates an object in virtual space. The results showed that there are differences between the intended and actual foot motions, especially when the tilt angle change was accompanied by a rotation angle change, which might be because of the joints whose axes of motion are nonparallel to the foot coordinate system, such as the talocalcaneal joint or Chopart joint. Next, an operating system considering the motion characteristics of the foot was proposed, and an experiment to verify its effectiveness was conducted. When the proposed conversion formula was used to calculate the intended foot motion based on the actual foot motion, the operability improved with respect to the required time and path-following accuracy while manipulating an object to the target posture and with respect to subjective operability.

INDEX TERMS Foot, human motion measurement, manipulation, operability.

I. INTRODUCTION

The upper limbs of the human body can perform motion with multiple degrees of freedom (DOFs) because of the joints of the shoulder, elbow, and wrist and changes in position and posture, which contribute to manipulating devices dexterously. As a usage example of such multi-DOF motion, an operating method for robot arms based on a master-slave system was proposed, in which a human arm is the master and a robot arm is the slave [1]–[9]. This method can allow users to intuitively operate devices, even when the user is unfamiliar with the device. This technology is expected to be useful, especially in the fields of living support and welfare, into which more robotic devices will be introduced [10]–[14].

The lower limbs are not only used for walking, but also have multiple DOFs, just like the upper limbs, thanks to the joints of the hip, knee, and ankle. This suggests that the lower limbs have the potential to perform the same operations as the upper limbs. As a major example of operation by lower limbs, 1-DOF operation, such as stepping on the acceleration or brake pedal of an automobile, is widely used. Operations involving two or more DOFs include a shoe-shaped interface for walking in virtual space by moving the center of gravity of the body [15], PC mice operated by foot [16]–[18], operation of electric devices by steps during jogging [19], and hands-free endoscope operation based on motion patterns of the foot [20]. Thus, several kinds of devices that use lower limb motions have been proposed, but their application to operating actual multi-DOF devices is limited compared to the upper limbs. In addition, past studies have not evaluated the characteristics of lower-limb motion or proposed an operating method considering such characteristics in the context of three-dimensional operation using lower-limb motion.

With that point in mind, the present paper focuses on the posture change of foot as a motion involved in lower limbs. More specifically, we examine the motion characteristics of the foot in 3-DOF posture manipulation by investigating how

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well an operator can move his foot according to his intention, taking the operation of a robot arm as an example. The human foot consists of many bones and joints, which realize the inter-segment motions and help the foot to face to an arbitrary direction, especially in walking [21]. However, the foot has limited movable range and lower motion accuracy compared to the hand in general, so that the operational performance of the foot is considered to be inferior to that of the hand. Therefore, in order to operate via foot motion, it is necessary to understand the disadvantages specific to foot and to support it with the appropriate technology. On the other hand, the need for such assistive technologies is low in the case of hand motion because the hands move almost as intended. This is the difference between hands and feet. It is thought that if the operation with the foot becomes easy, the choice of the operation method is broadened, which leads to the improvement of our daily life and the life of people with a disability in the upper limb.

In a previous study, we investigated the manipulation of the 3-DOF position and studied a system to manipulate the position of an object by the leg, the motion of which is measured by contactless sensors [22]. The result showed that unique characteristics occurred in the leg motion during operation, and that, in some cases, the actual motion of the leg was different from the intended motion. Furthermore, we proposed an operating method considering the motion characteristics and proved that the proposed system could improve operability compared to the conventional operating method through experiments. The present paper considers the posture change of foot in the same approach. We investigate the fundamental characteristics of foot motion and then construct an operation system considering these characteristics. In particular, a formula for converting the actual foot motion into the intended foot motion is proposed, and its effectiveness is verified experimentally.

II. EXPERIMENT TO INVESTIGATE THE CHARACTERISTICS OF FOOT MOTION DURING OPERATION

Some of the present authors have been proved that differences occur between the intended motions and actual motions when a device is operated using the motion of the leg, arm, or finger [3], [4], [22]. The same phenomenon can emerge in foot motion. This means that when people manipulate an object, such as a robot arm, by foot motion, the actual foot motion may vary from what is intended. In this section, an experiment is carried out in order to clarify the relationship between the intended and actual foot motions of the operator. We consider the situation in which operators, i.e., subjects, manipulate the posture of an object by foot. In an experiment, the subject views the motion of the object and moves his foot as if to manipulate an object. By measuring the motion of the foot, the relation to the motion of the object is discussed.

A. DEFINITION OF TERMS

Next, we define terms related to the motions of the foot and the object. Note that this study deals with the right foot.

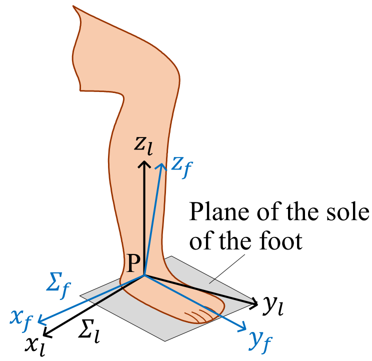

FIGURE 1. Leg coordinate system Σ_l and foot coordinate system Σ_f.

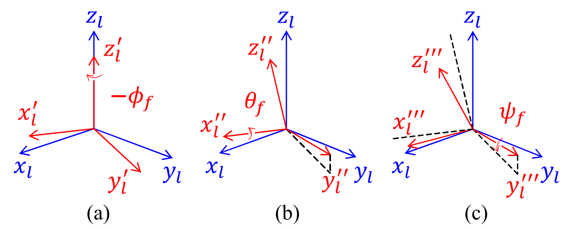

FIGURE 2. Representation of foot posture using three parameters.

1) LEG COORDINATE SYSTEM

As shown in Fig. 1, the leg coordinate system is a right-handed orthogonal coordinate system represented by Σ_l. Its origin is set at the center of the ankle joint P, and its three orthogonal axes are x_l, y_l, and z_l. The x_l axis is parallel to the rotation axis of the knee joint, and the positive direction is the direction from the internal side to the external side of the right leg. The z_l axis is on the major axis of the crus, and the positive direction is the direction from the ankle joint to the knee joint.

2) FOOT COORDINATE SYSTEM

As shown in Fig. 1, the foot coordinate system is a right-handed orthogonal coordinate system represented by Σ_f. Its origin is set at the center of the ankle joint P, and its three orthogonal axes are x_f, y_f, and z_f. The x_f axis crosses the foot laterally, and the positive direction is the direction from the internal malleolus to the external malleolus of the right leg. The y_f axis crosses the foot longitudinally, passing through the second toe, and the positive direction is the direction from the heel to the toe.

3) ROTATION ANGLE, ELEVATION ANGLE, AND TILT ANGLE

These angles represent the foot posture. As shown in Fig. 2, let us consider the situation in which the leg coordinate system is rotated in the following order. First, Σ_l is rotated around the z_l axis by angle ϕ_f, which results in the coordinate system $\Sigma_l'(\mathrm{P}-x_l'y_l'z_l')$ [Fig. 2(a)]. Next, Σ_l' is rotated around the x_l' axis by angle θ_f, which results in the coordinate system $\Sigma_l''(\mathrm{P}-x_l''y_l''z_l'')$ [Fig. 2(b)]. Finally, Σ_l'' is rotated around the y_l'' axis by angle ψ_f, which results in the coordinate system

FIGURE 3. Basic sitting position and standard posture. (a) Leg in the basic sitting position. (b) Foot in the standard posture.

$\Sigma_l'''(\mathrm{P}-x_l'''y_l'''z_l''')$ [Fig. 2(c)]. Assuming that Σ_l''' agrees with Σ_f, the posture of Σ_f as observed from Σ_l is represented by the combination of three angles $(\phi_f, \theta_f, \psi_f)$. In the following discussion, we represent the foot posture using these angles and refer to ϕ_f as the rotation angle, θ_f as the elevation angle, and ψ_f as the tilt angle.

4) BASIC SITTING POSITION

As shown in Fig. 3(a), this is the state in which a person sits straight with his hip joint and knee joint flexed at 90° on the sagittal plane. In the experiments, the leg of the subject is always fixed in this state during operation.

5) STANDARD POSTURE

The standard posture is the state in which Σ_l agrees with Σ_f, i.e., $(\phi_f, \theta_f, \psi_f) = (0, 0, 0)$, in the basic sitting position. Fig. 3(b) shows the foot of the operator in the standard posture.

6) IMAGINARY OPERATED OBJECT (IOO)

This is the object that the operator intends to manipulate. Here, the IOO is assumed to be a robot hand installed at the end of a robot arm. In the experiments, the IOO is displayed in virtual space on a computer screen.

7) FOREARM COORDINATE SYSTEM OF THE OBJECT

As shown in Fig. 4, the forearm coordinate system of the object is a right-handed orthogonal coordinate system fixed at the forearm of the robot arm and is represented by Σ_a. Its origin is set at the center of the joint between the arm and the hand, and its three orthogonal axes are x_a, y_a, and z_a. The joint between the arm and the hand of the designated robot arm is regarded as a spherical joint, which allows for posture changes around the three axes. The y_a axis is parallel to the forearm, and the positive direction is the direction to the tip of the forearm. The joint on the root side of the forearm is a rotational joint whose axis is perpendicular to y_a axis and parallel to the x_a axis. The forearm coordinate system of the object corresponds to the leg coordinate system of the operator.

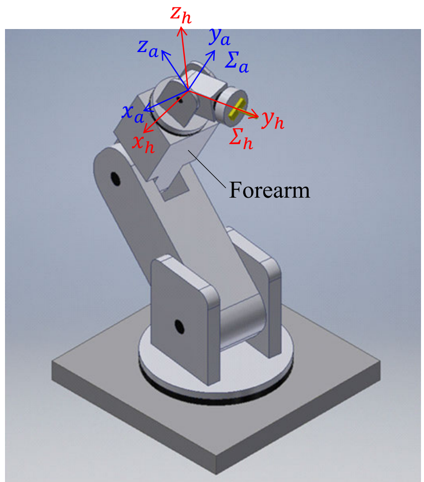

FIGURE 4. Forearm coordinate system of an object Σ_a and hand coordinate system of an object Σ_h.

8) HAND COORDINATE SYSTEM OF THE OBJECT

As shown in Fig. 4, the hand coordinate system of the object is a right-handed orthogonal coordinate system fixed at the hand of the IOO and is represented by Σ_h. Its origin is the same as that of the forearm coordinate system of the object, and its three orthogonal axes are x_h, y_h, and z_h. The x_h axis crosses the hand laterally, and the positive direction is the direction from the right side to the left side of the hand. The y_h axis crosses the hand longitudinally, and the positive direction is the direction from the root side to the tip side of the hand. The hand coordinate system of the object corresponds to the foot coordinate system of the operator. When the foot of the operator is in the standard posture, the hand coordinate system of the object agrees with the forearm coordinate system of the object.

9) YAW ANGLE, PITCH ANGLE, AND ROLL ANGLE

These angles represent the IOO posture. The relation between the forearm and hand coordinate systems of the object is the same as the relation between the leg and foot coordinate systems of the operator. The posture of the hand coordinate system of the object to the forearm coordinate system of the object is defined in the same manner as the posture of the foot coordinate system to the leg coordinate system, which is defined in terms of the rotation angle ϕ_f, elevation angle θ_f, and tilt angle ψ_f. Namely, the angles corresponding to these angles are set as the yaw angle ϕ, pitch angle θ, and roll angle ψ, respectively.

B. EXPERIMENTAL METHOD

1) OVERVIEW

As shown in Fig. 5, a subject sits in the basic sitting position facing a monitor showing the IOO posture change. The subject moves his foot in accordance with the IOO motion, assuming that he is operating the IOO by his foot. In other

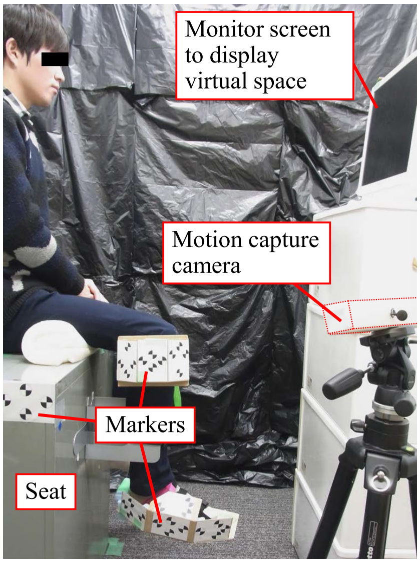

FIGURE 5. **Experimental environment.**

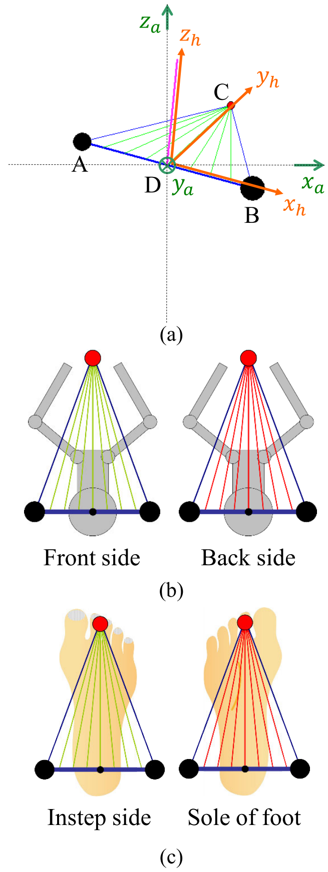

FIGURE 6. **(a) Imaginary operated object (IOO) in virtual space. (b) Relation between the IOO and the hand. (c) Relation between the IOO and the foot.**

words, the subject intends to move his foot so that its motion is the same as that of the IOO. The actual foot motion is measured under this condition. The IOO motion should reflect the intended foot motion of the subject. Then, the relation between the intended and actual foot motions is investigated. A real-time motion capture system is used for motion measurement. The marker of the motion capture system for the foot is fixed on the plate-like equipment that is attached to the subject's foot by belts to contact with the sole. The posture of the plate-like equipment is measured and treated as a foot posture.

2) IMAGINARY OPERATED OBJECT

In the experiment, the virtual space and the IOO shown in Fig. 6(a) are displayed to the subject. This figure describes the IOO hand as viewed from the y_a axis direction of the forearm coordinate system of the object. The horizontal and vertical dashed lines are on the x_a and z_a axes, respectively. The triangle ABC represents the IOO. The relation between the triangle ABC and the hand is shown in Fig. 6(b). Black spheres are fixed at vertices A and B, which indicate the root side of the hand, whereas a red sphere is fixed at vertex C, which represents the tip side of the hand. The joint connecting the arm and the hand is located at midpoint D between the two black spheres. From vertex C to side AB, lines are drawn radially in green on the front side of the hand and in red on the opposite side. Side AB is parallel to the x_h axis, and the line passing through vertex C and midpoint D is parallel to the y_h axis. The normal of the triangle ABC is parallel to the z_h axis. In order to facilitate the identification of the side of the hand, the segment normal to the triangle ABC passing through point D is drawn only on the front side of the hand. The depth position is displayed on a flat screen and so might be difficult to grasp in the virtual space. Therefore, the diameters of the spheres on the vertices are enlarged on the near side and shrunk on the far side. For example, Fig. 6(a) shows the red sphere is on the far side and the right black sphere is on the near side. The relation between the foot of the operator and the triangle ABC is shown in Fig. 6(c).

In the experiment, the IOO moves along 21 trajectories, as shown in Table 1. Fig. 7 shows examples of the IOO motion on the monitor. Only ϕ, θ, and ψ change in Motions 1 through 5, Motions 6 through 10, and Motions 11 through 15, respectively. In Motions 16 through 21, two of ϕ, θ, and ψ change at the same time. The IOO makes 10 round trips in each motion at the rate of one round trip every six seconds. The values of ϕ, θ, and ψ change sinusoidally.

3) MEASUREMENT METHOD OF FOOT MOTION

a: EXPERIMENT SETUP

As shown in Fig. 5, the operator sits on a seat and moves his foot intending to operate the IOO on the monitor. The motion of the foot is measured by a real-time optical motion capture system (Micron Tracker H3-60, Claron Technology Inc.), which can acquire the position and posture of the markers as captured by a camera in real time. The motion of the foot is calculated from the measurement results for the position and posture of the markers attached to the foot.

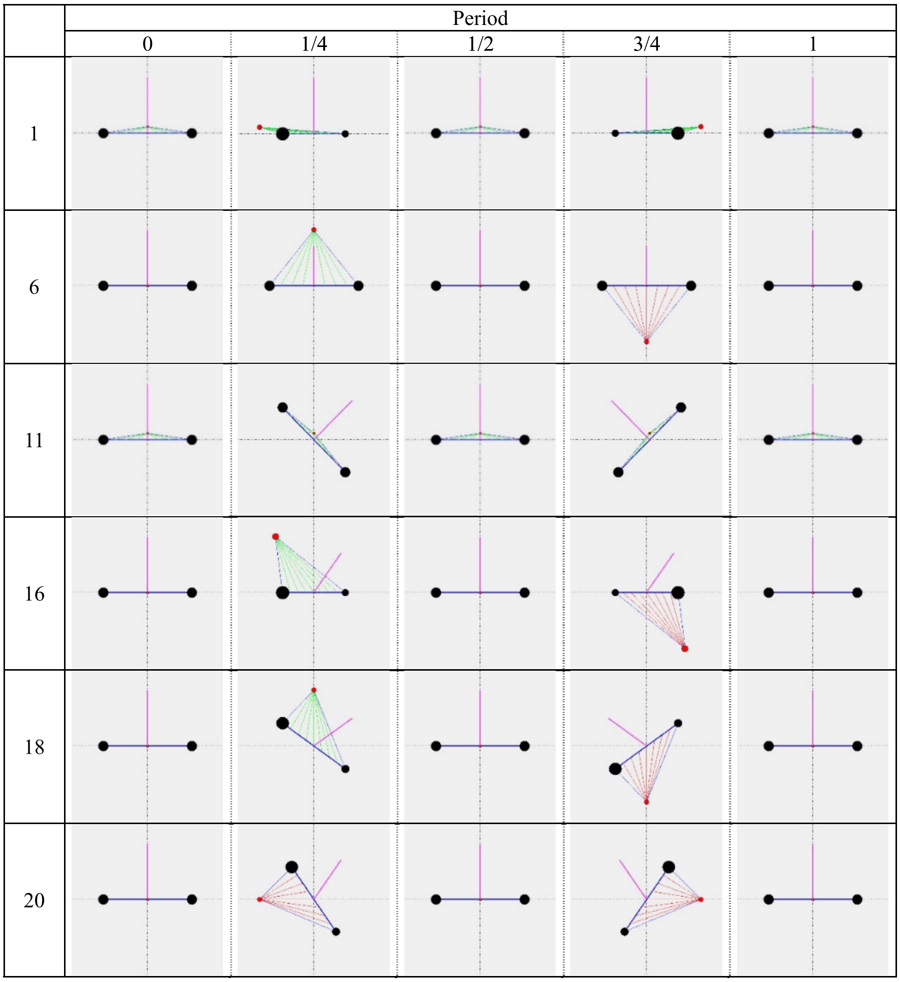

FIGURE 7. Examples of the IOO motion displayed to the subjects.

b: SUBJECTS

The subjects were ten adult males without disability or injury in the lower limbs. The average age of the subjects was 24.0 years, and the standard deviation was 1.1 years. This experiment and the experiment in Section IV were conducted with the approval of the Ethics Committee, Graduate School of Engineering, Kyoto University.

c: INSTRUCTIONS TO THE SUBJECTS

The relations between the hand and the IOO and between the foot and the IOO are explained to the subject using Fig. 6. With that in mind, the subject is instructed to move his right foot intuitively according to the motion of the IOO, as if he would manipulate the IOO by his right foot. In addition, the subject is required not to change the position of his right ankle during operation and not to look at his foot, but rather only at the monitor displaying the IOO motion. The subject does not have to match the posture of his foot to that of the IOO accurately because the IOO motion is so exaggerated for ease of visual understanding that the IOO motion might exceed the movable range of the human foot.

C. EXPERIMENTAL RESULTS AND DISCUSSIONS

The posture of the foot, i.e., the rotation angle ϕ_f, the elevation angle θ_f, and the tilt angle ψ_f, was calculated based on the measurement data. Fig. 8 shows the measurement results for one subject. The vertical axis of the graph indicates the magnitude of each parameter, and the horizontal axis indicates the period shown in Table 1. Although the IOO makes ten round trips for one motion in the experiment, Fig. 8 shows the result for five round trips, from the third to the seventh round trip, because the motions of the subjects may not be stable at the beginning or end of the IOO motion, and these trips are removed from the observations. Comparison between Fig. 8 and Table 1 for each motion suggests that the rotation angle ϕ_f, the elevation angle θ_f, and the tilt angle ψ_f of the foot change according to the change of the yaw angle ϕ, the pitch angle θ, and the roll angle ψ of the IOO shown to the subject. This result supports that the subject moved his foot intending to make the same motion as that of the IOO, following the instructions.

On the other hand, a closer look at Fig. 8 shows that, in some cases, the posture angles of the foot change even

TABLE 1. Motions of the IOO shown to the subjects.

Motion	Angle	Period 0	1/4	1/2	3/4	1
1	ϕ	0	45	0	-45	0
	θ	0	0	0	0	0
	ψ	0	0	0	0	0
2	ϕ	0	45	0	-45	0
	θ	15	15	15	15	15
	ψ	0	0	0	0	0
3	ϕ	0	45	0	-45	0
	θ	-15	-15	-15	-15	-15
	ψ	0	0	0	0	0
4	ϕ	0	45	0	-45	0
	θ	0	0	0	0	0
	ψ	15	15	15	15	15
5	ϕ	0	45	0	-45	0
	θ	0	0	0	0	0
	ψ	-15	-15	-15	-15	-15
6	ϕ	0	0	0	0	0
	θ	0	45	0	-45	0
	ψ	0	0	0	0	0
7	ϕ	0	0	0	0	0
	θ	0	45	0	-45	0
	ψ	15	15	15	15	15
8	ϕ	0	0	0	0	0
	θ	0	45	0	-45	0
	ψ	-15	-15	-15	-15	-15
9	ϕ	15	15	15	15	15
	θ	0	45	0	-45	0
	ψ	0	0	0	0	0
10	ϕ	-15	-15	-15	-15	-15
	θ	0	45	0	-45	0
	ψ	0	0	0	0	0
11	ϕ	0	0	0	0	0
	θ	0	0	0	0	0
	ψ	0	45	0	-45	0
12	ϕ	15	15	15	15	15
	θ	0	0	0	0	0
	ψ	0	45	0	-45	0
13	ϕ	-15	-15	-15	-15	-15
	θ	0	0	0	0	0
	ψ	0	45	0	-45	0
14	ϕ	0	0	0	0	0
	θ	15	15	15	15	15
	ψ	0	45	0	-45	0
15	ϕ	0	0	0	0	0
	θ	-15	-15	-15	-15	-15
	ψ	0	45	0	-45	0
16	ϕ	0	45	0	-45	0
	θ	0	45	0	-45	0
	ψ	0	0	0	0	0
17	ϕ	0	45	0	-45	0
	θ	0	-45	0	45	0
	ψ	0	0	0	0	0
18	ϕ	0	0	0	0	0
	θ	0	45	0	-45	0
	ψ	0	45	0	-45	0
19	ϕ	0	0	0	0	0
	θ	0	45	0	-45	0
	ψ	0	-45	0	45	0
20	ϕ	0	45	0	-45	0
	θ	0	0	0	0	0
	ψ	0	45	0	-45	0
21	ϕ	0	-45	0	45	0
	θ	0	0	0	0	0
	ψ	0	45	0	-45	0

*The units are degrees (°).

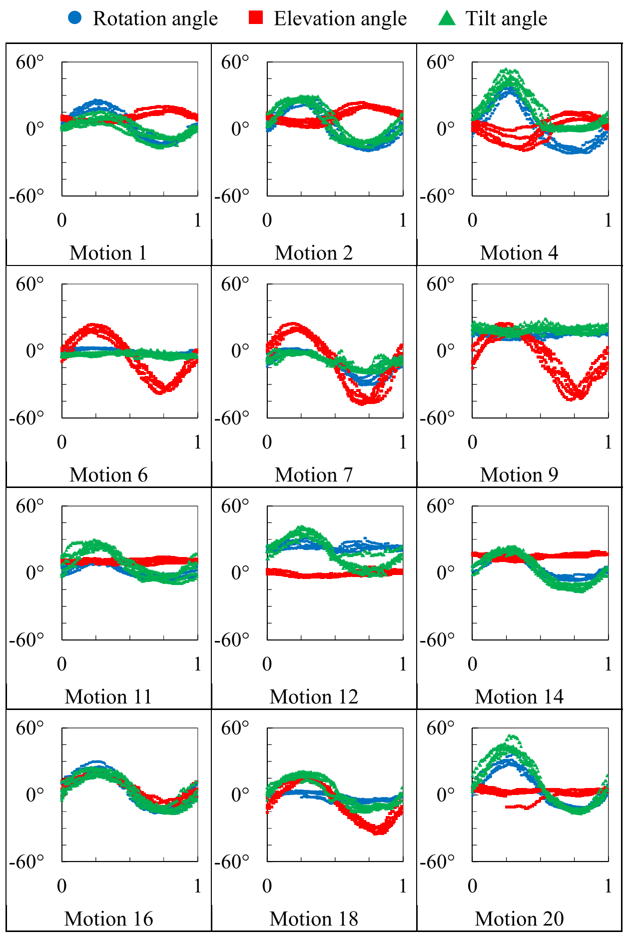

FIGURE 8. Examples of measurement results for the foot posture change.

when the corresponding angles of the IOO do not change. Focusing on Motion 1, for example, only the yaw angle ϕ changes in the IOO, whereas the rotation angle ϕ_f and the tilt angle ψ_f change along almost the same trajectory in the measured foot motion. In Motion 16, while the yaw angle ϕ and the pitch angle θ of the IOO change, the rotation angle ϕ_f, the elevation angle θ_f, and the tilt angle ψ_f of the subject foot appear to change. Some of the other motions, including motions not shown in Fig. 8 and results for other subjects, are also accompanied by changes in posture angles that are not observed in the IOO. Considering that these posture angle changes have the same periodicity as the IOO motion, they may arise not relevantly to the intention of the subjects but naturally according to the foot posture change. This means that in the situation in which the operator operates an object by his foot motion, the object may move differently from the intended motion if the posture change is commanded to the object closely following the foot motion.

Next, the relation between the foot posture and the unintended motion is examined. In the following discussion, the motion that arises unintentionally according to the foot posture change is referred to as*subordinate motion*. In Fig. 8, the posture angle change in the subordinate motion appears to be proportional to the posture angle change in the intended motion. Then, the coefficients of correlation between the rotation angle ϕ_f, the elevation angle θ_f, and the tilt angle ψ_f, represented by $\rho_{\phi\theta}$, $\rho_{\theta\psi}$, and $\rho_{\psi\phi}$, are calculated and shown in Table 2. The coefficients are calculated for each subject, and their maximum and minimum values are recorded in Table 2. Note that we used the sampling data in the range of $-30° \leq \phi, \theta, \psi \leq 30°$, because a subject may move his foot by force near the limit of the movable range. The table shows that the coefficients of correlation take different values in each subject in most cases, but there are cases of strong correlation in which the absolute value of the coefficient is larger than 0.7 among all subjects for some motions. Particularly, in motions in which the yaw angle ϕ changes (Motions 1 through 5, 16, 17, 20, and 21), the coefficient $\rho_{\psi\phi}$ becomes larger than 0.7, except in Motions 17 and 21, which means that there is a strong positive correlation between the rotation angle ϕ_f and the tilt angle ψ_f. Moreover, in Motion 17, $\rho_{\psi\phi} > 0.9$ is satisfied in nine of ten subjects. Furthermore, Motion 21 requires the rotation angle ϕ_f and the tilt angle ψ_f to be changed to the opposite direction, so that the magnitude of $\rho_{\psi\phi}$ becomes necessarily small. Considering these results, the typical subordinate motion tends to occur between the changes of the rotation angle ϕ_f and the tilt angle ψ_f in

TABLE 2. Coefficients of correlation between the posture angles in the measurement results for the foot posture change.

	Correlation coefficient (max/min)		
	$\rho_{\phi\theta}$	$\rho_{\theta\psi}$	$\rho_{\psi\phi}$
1	-0.53/-0.97	-0.40/-0.99	0.99/0.88*
2	0.49/-0.97	0.53/-0.98	0.99/0.92*
3	0.64/-0.81	0.67/-0.88	1.00/0.83*
4	-0.76/-0.96*	-0.72/-0.97*	0.99/0.75*
5	0.96/-0.97	0.96/-0.97	0.99/0.91*
6	0.95/-0.92	0.76/-0.79	0.93/0.06
7	0.95/-0.71	0.91/-0.40	0.98/-0.10
8	0.97/-0.96	0.60/-0.88	0.95/-0.04
9	0.89/-0.60	0.28/-0.84	0.90/-0.28
10	0.96/-0.28	0.94/-0.79	0.88/-0.50
11	0.56/-0.72	0.71/-0.80	0.95/0.62
12	0.74/-0.95	0.49/-0.93	0.97/-0.37
13	0.85/-0.37	0.91/-0.61	0.96/0.68
14	0.35/-0.78	0.73/-0.74	0.98/0.46
15	0.65/-0.63	0.78/-0.73	0.96/0.10
16	0.97/0.56	0.94/0.32	0.98/0.88*
17	-0.47/-0.96	-0.75/-0.96*	0.99/0.62
18	0.87/-0.83	0.85/-0.78	0.94/-0.56
19	0.94/-0.86	0.22/-0.96	0.94/-0.24
20	0.43/-0.89	0.47/-0.90	0.99/0.94*
21	-0.11/-0.94	0.13/-0.93	0.99/0.20

Note that * indicates strong correlation among all ten subjects.

the posture change of the human foot. One reason for such a subordinate motion might be because of the structure of the foot joint. The joints, such as the talocalcaneal joint and Chopart joint, which are dominant in the motion of the rearfoot, have axes of motion that are nonparallel to the x_f, y_f, and z_f axes of the foot coordinate system, so that these joints produce combined motion in posture change [23]. Therefore, it is assumed that the foot should also move subordinately in a direction other than the direction in which the subject intends to move.

In summary, when the posture of an object, such as a robot hand, is operated by foot motion and a command is made to the object exactly according to the foot motion, the object can move differently from the intention of the operator because of the subordinate motion of the foot, especially for cases in which the intended motion requires changing the yaw angle or the roll angle.

III. GENERATION FORMULAS FOR POSTURE COMMAND CONSIDERING THE MOTION CHARACTERISTICS OF THE HUMAN FOOT

In the previous section, it was revealed that there exist differences in the intended and actual foot motions and that the subordinate motion occurs according to the intended motion. In this section, formulas to convert the foot motion data into the motion command of the operated object are developed based on the result of the experiment carried out in the previous section.

In the conventional operating method using body motion, the operated object moves with the exact same motion as the motion of a body part of the operator. When this idea is applied to the posture operation by the foot, the parameters that represent the posture of the operated object are set to be the same as the counterparts of the foot posture. We refer to this as the simple conversion formula. When using the posture of the operated object $(\phi_o, \theta_o, \psi_o)$ and the posture of the operator's foot $\left(\phi_f, \theta_f, \psi_f\right)$, the formula is represented as follows:

$$\begin{cases} \phi_o = \phi_f \\ \theta_o = \theta_f \\ \psi_o = \psi_f. \end{cases} \tag{1}$$

In the present study, in contrast, the command generating method is considered to compensate the subordinate motions on the rotation angle ϕ_f and the tilt angle ψ_f, as revealed in the previous section. With respect to the rotation angle ϕ_f, for example, the rotation angle ϕ_f of the operator's foot is thought to depend on both the intended command of the yaw angle ϕ_o and the tilt angle ψ_f.

$$\phi_f = \phi_f\left(\phi_o, \psi_f\right) \tag{2}$$

Then, the variation of ϕ_f is given as follows:

$$d\phi_f = \frac{\partial \phi_f}{\partial \phi_o} d\phi_o + \frac{\partial \phi_f}{\partial \psi_f} d\psi_f \tag{3}$$

Next, we set $\partial\phi_f/\partial\phi_o = 1$ based on the simple conversion formula and assume that the subordinate motion is linear, i.e., $\partial\phi_f/\partial\psi_f$ is constant. At this time, the integral of (3) yields

$$\phi_f = \phi_o + \frac{\partial \phi_f}{\partial \psi_f}\psi_f \Leftrightarrow \phi_o = \phi_f - \frac{\partial \phi_f}{\partial \psi_f}\psi_f. \tag{4}$$

When considering the command of the roll angle ψ_o in the same way, the conversion formula results in

$$\begin{cases} \phi_o = \phi_f - \dfrac{\partial \phi_f}{\partial \psi_f}\psi_f \\ \theta_o = \theta_f \\ \psi_o = \psi_f - \dfrac{\partial \psi_f}{\partial \phi_f}\phi_f. \end{cases} \tag{5}$$

Based on the experimental results in Section III, appropriate values for $\partial\phi_f/\partial\psi_f$ and $\partial\psi_f/\partial\phi_f$ are derived. Here, we focus on the motions in which there is a strong correlation between the rotation angle ϕ_f and the tilt angle ψ_f among all subjects in Table 2 (Motions 1 through 5, 16, and 20) and calculate the means of $\partial\phi_f/\partial\psi_f$ and $\partial\psi_f/\partial\phi_f$. In this way, the means of all subjects are given as $\partial\phi_f/\partial\psi_f = 1.14$ and $\partial\psi_f/\partial\phi_f = 1.63$, the standard deviations of which are 0.53 and 0.96, respectively.

On the other hand, when using the proposed conversion formula in practice, we should take into consideration that the situation of the measurement experiment in Section II may differ from the situation in which the operator actually manipulates the object by foot motion. In the experiment of

Section II, the subject moves his foot without seeing it, so that he cannot correct the motion based on visual feedback, even when the foot moves in an unintended way. When actually operating the object, however, the operator can see the object motion, so that the operator can correct the foot motion spontaneously when he notices unintended motion. In this case, if the conversion formula derived above is used as is, there is a concern that the term correcting the subordinate motion affects the object to too great an extent. In other words, there is a possibility that the operability becomes worse because of the correcting terms for the motion of the operated object due to their effects. A previous study, which investigated a method by which to manipulate the object position using leg motion, showed that the operability was improved when the effect of the correcting terms was restrained to a certain degree [22]. Therefore, in the posture change of the foot also, the values of $\partial\phi_f/\partial\psi_f$ and $\partial\psi_f/\partial\phi_f$ should be smaller than those calculated from the data of the measurement experiment. Then, coefficients k_ϕ and k_ψ are introduced to adjust the effects of the correcting terms, as follows:

$$\begin{cases} \phi_o = \phi_f - k_\phi \dfrac{\partial\phi_f}{\partial\psi_f}\psi_f \\ \theta_o = \theta_f \\ \psi_o = \psi_f - k_\psi \dfrac{\partial\psi_f}{\partial\phi_f}\phi_f \end{cases} \tag{6}$$

where $0 \leq k_\phi, k_\psi \leq 1$.

IV. EVALUATION EXPERIMENT OF THE PROPOSED OPERATING METHOD

In this section, an evaluation experiment is conducted in which the operator actually operates the IOO using the conversion formula considering the motion characteristics of the human foot proposed in the previous section. The effectiveness of the proposed formula is verified through a comparison with the simple conversion formula.

A. EXPERIMENTAL METHOD

1) EXPERIMENTAL DEVICES

The experimental environment is similar to that of the experiment in Section II, but is different in that the subject can operate the IOO through the monitor by posture changes of the foot. The IOO is displayed in virtual space on the screen. The posture of the foot was measured by a real-time motion capture system, and the IOO was moved to the posture corresponding to that of the foot. In this way, the subject could operate the IOO by his foot.

2) EXPERIMENTAL DETAILS

The operation method is evaluated based on a game that involves manipulating the posture of the IOO. In the game of this experiment, a target appears with a random posture in the virtual space, and the operator changes the posture of the IOO to match the target posture. As shown in Fig. 9(a), the IOO is described by the triangle with the blue sides, and the target is described by the triangle with the light blue sides. Each triangle has spheres on the vertices and the normal segment. When the postures of the IOO and the target agree with each other, as shown in Fig. 9(b), the next target appears and the previous target changes to a triangle with the black sides, as shown in Fig. 9(c). At the same time, an orange segment appears, connecting the tips of the previous and present target triangles. This is the target path that the tip of the IOO triangle should follow. When the designated number of targets has been reached, the game ends. The subject attempts to finish the game as quickly as possible and to operate the IOO so as to follow the indicated target path as closely as possible.

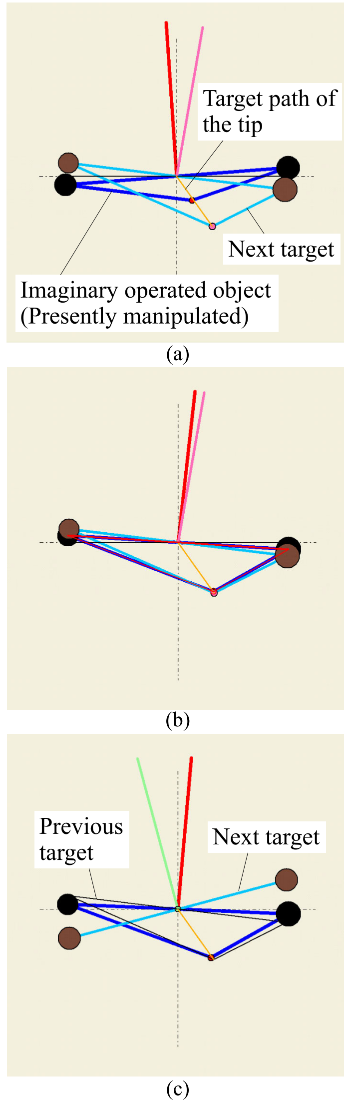

FIGURE 9. Imaginary operated object, the previous and next targets, and the target path in the virtual space.

The operability is evaluated based on time and accuracy. The operability is considered to improve as the time required to reach the target posture becomes shorter. Then, the time used to finish a game is measured and examined. The operability is also considered to improve as the accuracy of following the target path increases. The accuracy is evaluated based on the time mean value of the distance between the tip of the IOO and the target path. When this distance is smaller, the path of the tip is closer to the target path, i.e., the error is smaller, so that the accuracy is evaluated as being higher.

In this experiment, seven targets appear in one game. Regarding the appearance pattern, two types of games are prepared. The first type has one DOF, and the target posture $(\phi_t, \theta_t, \psi_t)$ is always chosen within the range of $-20° \leq \phi_t \leq 10°$ and $-2° \leq \theta_t, \psi_t \leq 2°$. In this game, the subject mainly changes the rotation angle ϕ_f. The goal is to verify the fundamental effectiveness of the corrected conversion formula because the subordinate motions mainly occurred in motions with a changing yaw angle ϕ in the experimental results of Section II. In this experiment, ten types of 1-DOF games are conducted. The other type of game has three DOF. The appearance range of the target is $-20° \leq \phi_t \leq 10°$, $-30° \leq \theta_t \leq 15°$, and $-15° \leq \psi_t \leq 25°$ and the appearing posture is chosen so as to prevent the unevenness of patterns. The appearance range is decided based on the experimental results described in Section II, referencing the ordinary movable range of the foot [23], [24] so as not to generate unreachable targets. In this experiment, 25 kinds of 3-DOF games are conducted.

In this experiment, the IOO and target postures are judged to be in agreement when the relation between the IOO posture $(\phi_O, \theta_O, \psi_O)$ and the target posture $(\phi_t, \theta_t, \psi_t)$ satisfy the following condition for one second continuously:

$$\begin{cases} |\phi_o - \phi_t| \leq 3.5° \\ |\theta_o - \theta_t| \leq 5.0° \\ |\psi_o - \psi_t| \leq 4.5°. \end{cases} \quad (7)$$

This condition is set in order to ignore cases in which the IOO posture unintentionally agrees with the target posture. The range varies depending on the parameters in (7) because the movable range of the foot in the direction corresponding to each parameter is different. In the experiment, in order to make facilitate the subject in visually recognizing that the posture of the IOO has agreed with the target posture, the color of the sides of the IOO triangle change to red, as shown in Fig. 10(b), when these postures are in agreement, i.e., when the condition of (7) is satisfied.

The process of the game from the start to finish is as follows.

1) First, a target (start target) appears at the posture $(\phi_t, \theta_t, \psi_t) = (0, 0, 0)$ in the virtual space. The time measurement starts when the subject manipulates the IOO to makes its posture match the start target posture. At the same time, the first target and the target path appear, and the start target changes to black.
2) The subject changes the IOO posture so as to follow the target path as closely as possible. When the posture of the IOO agrees with that of the first target, the second target and the next target path appear, and the color of the first target changes to black. The new target and target path then appear successively in the same way.

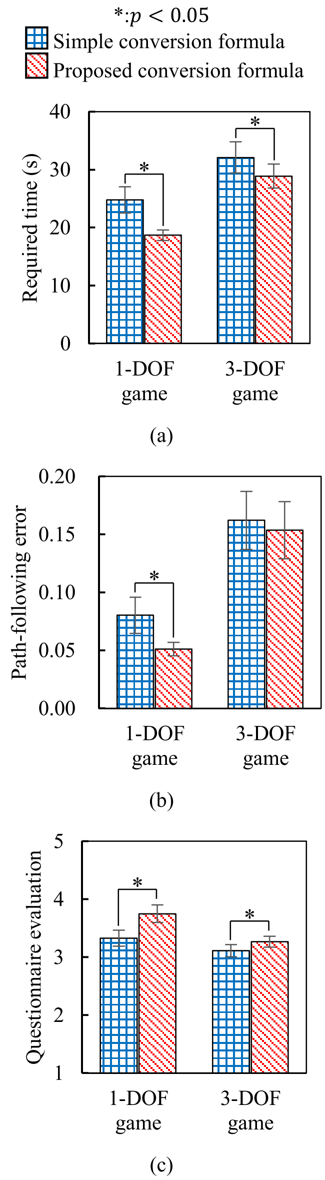

FIGURE 10. **Results of the evaluation experiment. (a) Required time. (b) Path-following error (dimensionless). (c) Questionnaire evaluation (dimensionless).**

3) When the posture of the IOO agrees with that of the seventh target, the game ends, and time measurement is stopped.
4) The results are evaluated based on the time required to complete the game and the accuracy of the target path following.

3) EXPERIMENTAL PROCEDURE

The subjects are the same ten males who participated in the experiment described in Section II. Each subject manipulates the posture of the IOO in the virtual space displayed on a screen and plays the games. The two conversion formulas, in (1) and (6), are used. For each formula, 35 of each of the abovementioned games are played. In other words, each subject plays 70 games. The order of the 70 games is random and differs for each subject. In this experiment, we focus on the correction of the roll angle ψ_o rather than the yaw angle ϕ_o from the view of verifying the fundamental effectiveness of the proposed conversion formula. This is because the change of the tilt angle ψ_f, corresponding to the roll angle ψ_o, requires more complicated joint motion than the change of the rotation angle ϕ_f, corresponding to the yaw angle ϕ_o [23], and accurately changing the tilt angle ψ_f is considered to be more difficult. Therefore, $k_\phi = 0$ and $k_\psi = 0.245$ are applied to the proposed conversion formula, i.e., (6), used in this experiment

The procedure of the game was explained to the subjects. At the same time, the subjects were instructed to operate the IOO as quickly and as accurately as possible because the results of the game were evaluated based on the required time for one game and the accuracy of target path following. On the other hand, the subjects were not informed of the two types of conversion formulas, or even that there exist two types of formulas. Before the experiment, the subject experienced a practice game so that the subjects could become familiar with the display of the virtual space. The practice game is basically the same as the actual game, but its seven targets are arranged as far from the standard posture as possible so as to confirm that the movable range of the subject foot is large enough to complete the games in the experiment. After finishing each game, each subject was asked whether he could operate the IOO as intended using a five-grade evaluation, in which one indicates ''poorly'' and five indicates ''well''.

B. EXPERIMENTAL RESULTS AND DISCUSSIONS

Fig. 10 shows the experimental results. The figure shows the results for (a) the required time, (b) the path-following error, and (c) the questionnaire evaluation along with the means and the 5% confidence intervals of all subjects. The path-following error is indicated by a dimensionless quantity when the height of the IOO triangle is set as 1. Compared to the results of the simple conversion formula, the results of the proposed conversion formula show that the time is reduced by approximately 25% for the 1-DOF games and by approximately 10% for the 3-DOF games. According to the Mann-Whitney U test, these differences are statistically significant. The error is approximately 36% smaller in the 1-DOF games and approximately 5% smaller in the 3-DOF games. The difference in the 1-DOF games is statistically significant. The questionnaire evaluation on operability becomes approximately 13% higher in the 1-DOF games and approximately 5% higher in the 3-DOF games, each of which has a statistically significant difference. In summary, the proposed conversion formula is verified to be effective in terms of time, accuracy, and questionnaire results for 1-DOF games and in terms of time and questionnaire for the 3-DOF games.

As shown in Section II, there exist differences between the intended and actual motions when people move their feet. In the experiment conducted in Section II, each subject moved his foot while viewing the motion of the IOO. Therefore, the subject could not recognize the difference between the actual and intended foot motions and thereby correct the motion of his own foot. In contrast, in the evaluation experiment in this section, the subject could see the motion of the object operated by his own foot and use the feedback of the difference between the intended and actual motions of the object. Considering the differences of these experimental situations, the simple conversion formula may be evaluated to be as good as or better than the proposed conversion formula. However, the experimental results showed that the proposed conversion formula provided better results. Consequently, an effective conversion formula was constructed whether visual feedback is feasible or not.

Comparing the results of the 1-DOF and 3-DOF games, the improvement ratios by the proposed conversion formula are higher in the 1-DOF games for every evaluation point. Therefore, the effectiveness of the proposed conversion formula is more remarkable in the 1-DOF games. This result agrees with the expectation because the targets in the 1-DOF games are arranged considering the situation in which the subordinate motions are likely to occur. Moreover, the effectiveness of the proposed conversion formula is validated to a certain degree even for the 3-DOF games, but not so much as in the case of the 1-DOF games. Thus, the negative effects of the proposed formula with respect to the operation can be sufficiently small. Then, it is expected that the operability can be further improved, even for the three-dimensional motions, if the correction of the yaw angle ϕ_o, which is not used in the experiment, is introduced.

V. CONCLUSION

The lower limbs of the human body, like the upper limbs, have multiple DOFs, so that there is a possibility of using the lower limbs for the operation of multi-DOF devices, such as a robot arm. The authors focused on the potential for operation by the lower limbs and constructed an operating system in which the operator manipulates devices based on the motion of the lower limbs. The present paper discussed the situation in which the posture of the object was manipulated by the posture change of the foot and investigated the degree to which the foot of the operator moved in accordance with his intention in order to clarify the motion characteristics of the foot. An operating system considering these characteristics was proposed, and an experiment to verify its effectiveness was conducted. The following results were obtained.

1) The relation between the intended and actual motions of the subject foot was investigated in an experiment assuming the situation in which the subject manipulates the object posture by his foot motion. The results revealed that differences between the intended and actual motions of the subject foot occurred and that a tilt angle change was accompanied by a rotation angle change when the subject intended to change the rotation angle of the foot.
2) Considering the motion characteristics of the foot shown in the experiment, a conversion formula to

calculate the intended foot motion of the operator based on the actual foot motion was developed.

3) An evaluation experiment to compare the proposed conversion formula and the conventional simple conversion formula was carried out. As a result, the proposed conversion formula was evaluated to be as good as or better than the simple conversion formula in terms of the required time and path-following accuracy while manipulating the object to the target posture, as well as in terms of subjective operability. Finally, the effectiveness of the proposed conversion formula for the operation was verified.

The difference between the intended motion and the actual motion of the hand is considered to be small, but the difference of the foot is significant. Therefore, it is necessary to understand the difference between the intended and actual motions and to support it by the method proposed in this paper in the case of an operation via foot motion.

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