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Human-powered vehicle capable of movement in the longitudinal and lateral directions

Hiroki KATO*, Masaharu KOMORI* and Tatsuro TERAKAWA*

*Department of Mechanical Engineering and Science, Kyoto University

Kyoto daigaku-katsura, Nishikyo-ku, Kyoto-shi, Kyoto 615-8540, Japan

E-mail: terakawa@me.kyoto-u.ac.jp

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Abstract

Human-powered vehicles, especially conventional wheelchairs, are essential tools for people with lower body disability. But their movement in a lateral direction is limited or impossible, which burdens users who want to change directions, especially in a narrow space. Thus, a human-powered vehicle that can move in a lateral direction is required. To move in any direction, many motor-driven omnidirectional vehicles have been proposed, but humans cannot manually power their mechanisms. To solve this problem, we are developing a human-powered vehicle, that is, driven by hands of the rider, that can move in both the longitudinal and lateral directions. This paper proposes such a vehicle, which has a mechanism to move in the lateral direction like people can do while walking. We designed it so that riders can operate its mechanism by analyzing the space reachable by the rider's palms where they can effectively exert power. We constructed a prototype and conducted experiments to confirm that the vehicle moves as expected with relatively low effort. In the experiments, we confirmed the validity of vehicle operation by comparing the moving time of the vehicle with and without the lateral translation function for different travel distances and passage widths. Our results showed that the proposed vehicle moves more quickly or requires shorter moving distance in comparison with a conventional wheelchair because of the lateral movement function. In addition, we found that the threshold for utility of the function is whether the passage width is larger than the vehicle diagonal length.

Keywords : Lateral direction, Human-powered, Vehicle, Wheelchair, Omni wheel

1. Introduction

Human-powered wheelchairs are an important means of transportation for physically challenged people, elderly people, and people with lower body disability. Self-powered mobility is essential for increasing their opportunities to participate in society. Wheelchairs are prescribed for purposes of nursing or caring, and the demand is expected to become larger as the elderly population increases in many countries, including Japan. Human-powered vehicles have advantages of low power and high safety because they do not move unless someone applies force (Watanabe et al., 2018). Wheelchairs also contribute to health and fitness because riders must use their upper body, which provides a measure of physical conditioning. Thus, human-powered vehicles, such as wheelchairs, are desirable for various reasons. However, conventional wheelchairs have mobility limitations. They can easily move in the longitudinal direction and turn, but they cannot move in the lateral direction. To move in the lateral direction, a wheelchair must first change its direction, sometimes by combining repeated turns and longitudinal movements, especially in a narrow space. Even if it moves a little distance in the lateral direction, it must change its direction each time, which is a burden on the riders because of the physical effort. These problems reduce their usability. Thus, a new vehicle is needed that is driven only by the physical effort of the rider and that can move in the longitudinal direction but also move in the lateral direction without turning. However, there have been no reports of self-powered vehicles that can realize those motions.

In the field of motor-driven vehicles, omnidirectional vehicles, which can move in any direction and turn, have been proposed. Grabowfecki (1919) initially developed an omni wheel that has rotatable outer rollers along the outer circumference of the wheel. The omni wheel actively moves in one direction by rotating the main body of the wheel

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and passively moves in the other direction by rotating the outer rollers. Three omni wheels can constitute an omnidirectional vehicle (Asama et al., 1996; Paromtchik et al., 1999). Based on the same principle as that of the omni wheel, some omnidirectional wheel mechanisms have been developed, such as the Swedish wheel that has outer rollers arranged obliquely (Erland, 1974), an active omni wheel whose main body and outer rollers are both actively driven by using a differential gear mechanism (Komori et al., 2016), and an omnidirectional wheel with dual rings that are combined as a sphere driven by helical gears (Fujimoto et al., 2018). Another example that uses principles different from these mechanisms have also been developed: an omnidirectional vehicle in which the relative positions of the three wheels are variable (Terakawa et al., 2018), an omnidirectional vehicle that has caster type wheels with an offset between the steering axis and the ground contact point (Campion et al., 1996), and other various types of omnidirectional vehicles (Pin and Killough, 1994; West and Asada, 1995; Wada and Mori, 1997; Isoda et al., 1999; Yamashita et al., 2003; El-Shenawy et al., 2006; Mourioux et al., 2006; Tadakuma et al., 2008; Kumagai and Ochiai, 2008; Ren and Ma, 2015; Maeda and Ando, 2015; Masuda et al., 2017; Kato and Wada, 2018).

One way to realize a human-powered vehicle movable in the longitudinal and lateral directions is to apply the mechanism of one of these motor-driven omnidirectional vehicles to a wheelchair, but it is difficult. These omnidirectional vehicles use three or more motors to drive the wheels accurately and realize omnidirectional movement, but it is difficult for the riders to rotate three or more wheels with their hands simultaneously and accurately. To solve this problem, this study developed a human-powered vehicle movable in the longitudinal and lateral direction that the rider can drive it with his or her hands. In this paper, we first propose a mechanism to move in the lateral direction by simple repetitive operation and explain its structure and motion. Next, we analyze the conditions required to operate the proposed mechanism by hand and design the vehicle based on these conditions. Finally, we describe development and testing of a vehicle prototype to confirm that the vehicle can move as expected and to validate the mobility in the lateral direction.

2. Principle and mechanism of human-powered vehicle movable in longitudinal and lateral directions

2.1 Principle and structure of proposed vehicle

Figure 1 shows an overview of the proposed vehicle. This vehicle is composed of the main body, two front wheels, two rear wheels, brakes mounted on the rear wheels, linear guides connecting the rear wheels and the main body, and handles to operate the rear wheels. The rear wheels are driving wheels, while the front wheels are supporting wheels. The state of the outer rollers of the rear wheels can be switched between a state in which the rotation of the outer rollers is forbidden (braking state) and a state in which rotation is allowed (free-wheeling state). The switching operation is performed by using the operating handles. The linear guides are installed inside the main body, and their extension and retraction enable the rear wheels to move in a lateral direction relative to the main body. The extension/retraction operation is also controlled by the operating handles. Because the design of the vehicle developed in this study was primarily aimed at confirming the fundamental effectiveness of the proposed mechanism, the vehicle's form is dissimilar to that of a conventional wheelchair.

Next, we explain how to operate the vehicle. Longitudinal movement and turning are accomplished by grasping and rotating the main bodies of the rear wheels on the sides of the vehicle, in the same way as a conventional wheelchair. The vehicle moves in the longitudinal direction by rotating both wheels in the same direction at the same speed, and it can turn in place by rotating the wheels in opposite directions at the same speed. Lateral movement is accomplished by operating the brakes and the linear guides mounted on the rear wheels. The operation method is explained in Fig. 2, which depicts the main body, rear wheels, and linear guides of the vehicle schematically and shows the lateral movement as seen from behind. When the vehicle is not moving laterally, the outer rollers of both rear wheels are in the braking state [Fig. 2(a)]. Let us consider the situation where the vehicle moves laterally to the right from this state. First, the rider sets the outer rollers of the right wheel in the free-wheeling state, and then pushes the right wheel to the right. At this time, the outer rollers of the right wheel are in the free-wheeling state and can rotate, so that the right wheel moves to the right along as its linear guide extend. Meanwhile, the outer rollers of the left wheel are in the braking state, which prevents the left wheel from moving in the lateral direction. As a result, only the right wheel moves to the right [Fig. 2(b)]. Next, after applying brakes to the outer rollers of the right wheel, the rider pulls the right rear wheel and pushes the left rear wheel. Then, the main body of the vehicle moves to the right [Fig. 2(c)]. At this time, neither the right nor left wheels move in the lateral direction because the brakes prevent the rotation of the outer

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rollers, and only the main body moves. After that, the rider places the outer rollers of the left wheel in the free-wheeling state and pulls the left rear wheel to the right. At this time, because the outer rollers of the right wheel are in the braking state, only the left wheel moves to the right [Fig. 2(d)]. After completing the lateral movement of the left rear wheel, the rider applies the brakes to the outer rollers of the left wheel [Fig. 2(e)]. By repeating the operations shown in Fig. 2, the vehicle can move an arbitrary distance to the right. Movement to the left is accomplished by the same operation in the opposite direction.

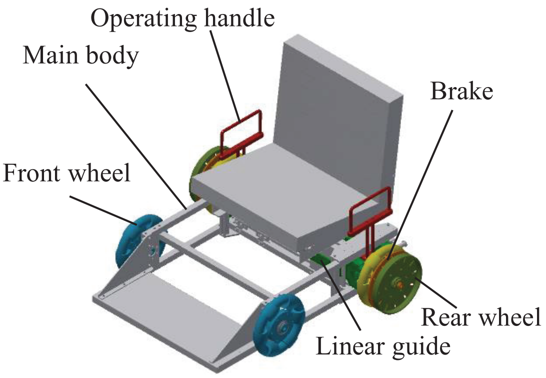

Fig. 1 Overview of the proposed human-powered vehicle movable in the longitudinal and lateral directions

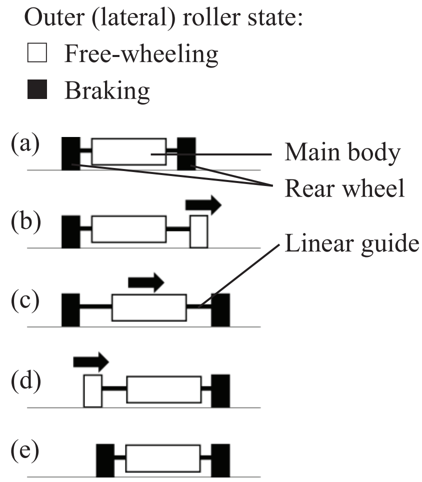

Fig. 2 Lateral movement method of the proposed vehicle

2.2 Design of components of proposed vehicle

This section explains the details of every part of the proposed vehicle. The qualitative specifications of this vehicle are as follows: First, the vehicle can perform the lateral movement in addition to the longitudinal movement and turn like a conventional wheelchair. Second, a person can ride on and operate the vehicle. The vehicle should be operated by the rider's upper limbs intuitively at the same level of walking, especially when moving in the lateral direction. Third, the riders can operate the vehicle easily within human power. The assumed rider is an adult with 180 cm in height and 80 kg in weight.

2.2.1 Rear wheels and brakes

To enable the proposed vehicle to move in the longitudinal and lateral directions, omni wheels are used for the front and rear wheels. We selected the omni wheel that has barrel-shaped outer rollers around the circumference of the wheel main body as shown in Fig. 3(c). Indeed a double-layered type of omni wheel that has outer rollers arranged alternately (Asama et al., 1996) is another option, but this type of the omni wheel has a disadvantage of large wheel width in the axial direction. Therefore, we selected the one shown in the figure. Each wheel is installed so as to let its main body and outer rollers rotate freely. As stated in Section 2.1, the rider drives the rear wheels with his or her hands. A hand rim is fixed to the main body of the rear wheels to allow the rider to rotate them by hand, just as in a conventional wheelchair [Fig. 3(a)]. The rider grasps this hand rim to rotate the main body of the rear wheel.

Brakes are mounted on the rear wheels to limit the rotation of the outer rollers, that is, prevent lateral movement. The brake is composed of a disk and brake pads, and the disk is pushed toward the rear wheel by a spring [Fig. 3(b)]. The brake pads are pressed to the outer rollers of the wheel, which generates friction force to establish a braking state [Fig. 3(c), (d)]. We use the unilateral brake rather than the bilateral brake because the latter one is so complex that it is difficult to install. When the disk separates from a rear wheel by operation of the control handle, as described below, the brake pads separate from the outer rollers, and the brake is released [Fig. 3(e)]. Because a spring applies the brake continuously, the rear wheels are kept in the braking state unless the rider operates the brake release. Therefore, the brakes are applied while the proposed vehicle moves in the longitudinal direction and turns, whereas they are released only while the vehicle moves in the lateral direction, as shown in Fig. 2. This is because the proposed vehicle is

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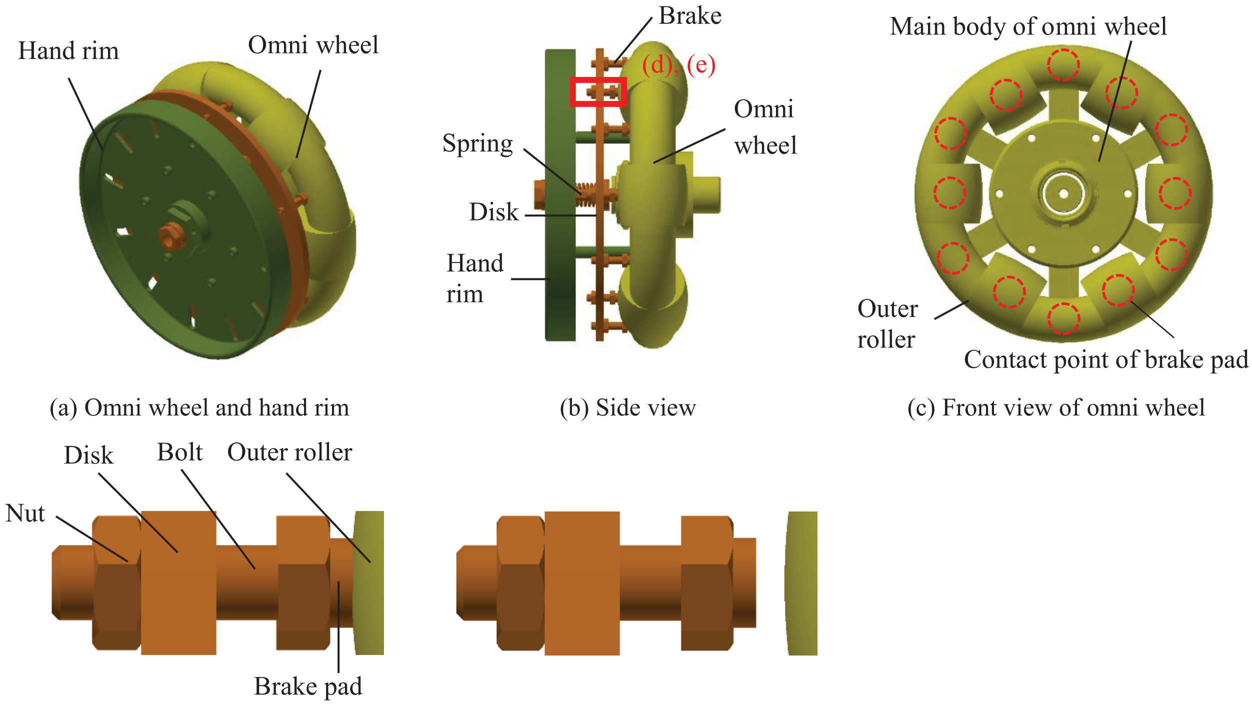
supposed to be used like a conventional wheelchair in most cases but be capable of moving in the lateral direction when necessary. The distances between the brake pads and the outer rollers can be adjusted by bolts and nuts.



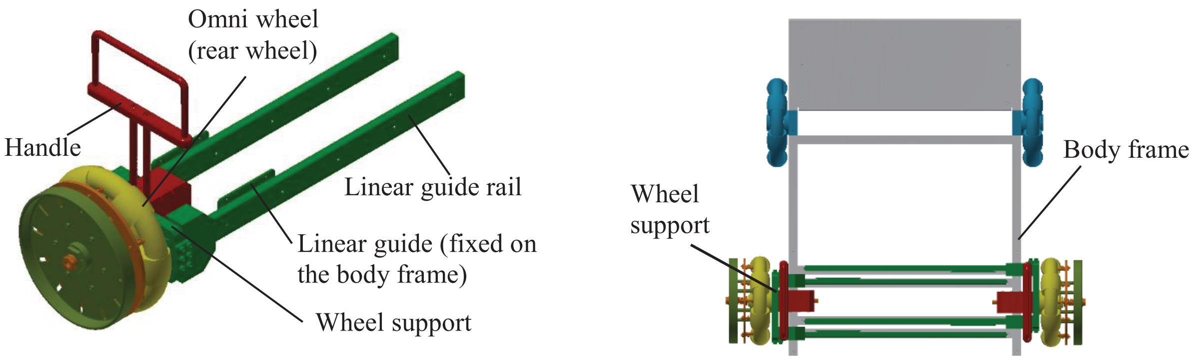
(a) Omni wheel and hand rim (b) Side view (c) Front view of omni wheel

(d) Braking state (e) Free-wheeling state

Fig. 3 Rear omni wheel and brake

2.2.2 Linear guides

As shown in Fig. 2, the right and left rear wheels need to move independently in the lateral direction relative to the main body to enable lateral movement. Thus, a linear guide connects each rear wheel and the main body to enable this relative movement. As shown in Fig. 4(a), the rails of the linear guides are fixed to the wheel support. When the linear guides are retracted, these rails slide into the main body of the vehicle. The right and left linear guides are staggered longitudinally to avoid interference with each other [Fig. 4(b)].



(a) Omni wheel and linear guides (b) Arrangement of linear guides (top view)

Fig. 4 Linear guides configuration

2.2.3 Operating handles

The operating handles allow the rider to control lateral movement. The handles must perform two functions, namely to switch the outer roller state between free-wheeling and braking and to move the linear guides to the left/right. Because the brake and linear guide operation are needed for lateral movement, it is desirable that one control handle on each side perform both these functions to reduce the effort needed to shift the omni wheel operation from one

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mode to the other.

When considering the operation method for fulfilling this requirement, we note the foot motion when people walk laterally without turning. Figure 5 shows rightward movement of a person as seen from behind. Their right foot is lifted first to allow the foot to move freely in the lateral direction [Fig. 5(b)]. Then, the foot is moved to the right [Fig. 5(c)] and placed on the ground at the desired point [Fig. 5(d)]. Here, we try to associate this series of movements with the linear guide movement of the proposed vehicle. Figure 6 shows this method also from behind. First, the brake of the rear wheel is released by lifting the operating handle to enable the wheel to move laterally [Fig. 6(b)]. While keeping the handle lifted, the rider pushes it outward and moves the wheel to the right [Fig. 6(c)]. After that, the rider lowers the handle after the intended distance has been traveled to apply the brake [Fig. 6(d)]. In summary, the rider operates the brake by moving the handle in the vertical direction and operates the linear guides by moving it in the lateral direction. Details of the operating handle are shown in Figs. 4(a) and 7, and lever is used as the operating handle. As Fig. 7(b) shows, the brake is released when the lever is lifted and applied when the lever is lowered (resting position). The rear wheel can be moved laterally by moving the lever to the left or right while it is pulled up.

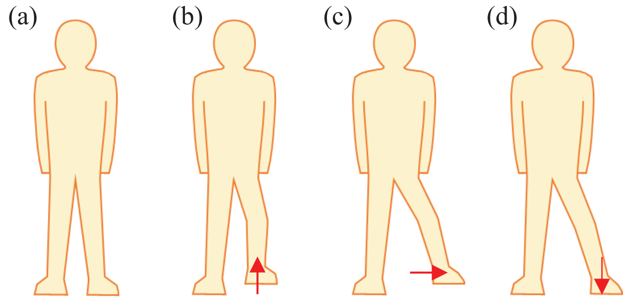

Fig. 5 Person moving to the right as seen from behind

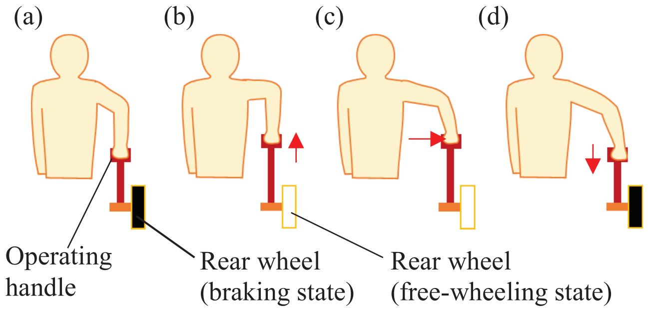

Fig. 6 Lateral movement method of proposed vehicle

More details of the operating handle mechanism are explained using Fig. 7. As mentioned in Section 2.2.1, the rear wheel brake is applied or released by moving the brake pads fixed to the disks in the axial direction. To change the vertical motion of the lever into the axial motion of the disk, a rack-and-pinion mechanism is used. A rod is fixed at the center of the disk and it runs through the axle shaft of the rear wheel. The rack is formed by teeth on the rod and the lower part of the lever. The rack is connected through the pinions to change the direction of movement. The disk is pulled in the direction away from the wheel when the lever is lifted and the brake is released due to this mechanism as shown in the right side of Fig. 7(b). Instead of the rack-and-pinion mechanism, the linkage mechanism can be used to accomplish the same function, but it requires space enough for the link to move. In order to make the brake system compact, we select the rack-and-pinion mechanism. The disk is pushed toward the wheel when the lever is released because of the gravity force on the lever and the restoring force of the spring mounted on the disk; then, the brake is applied as shown in the left side of Fig. 7(b).

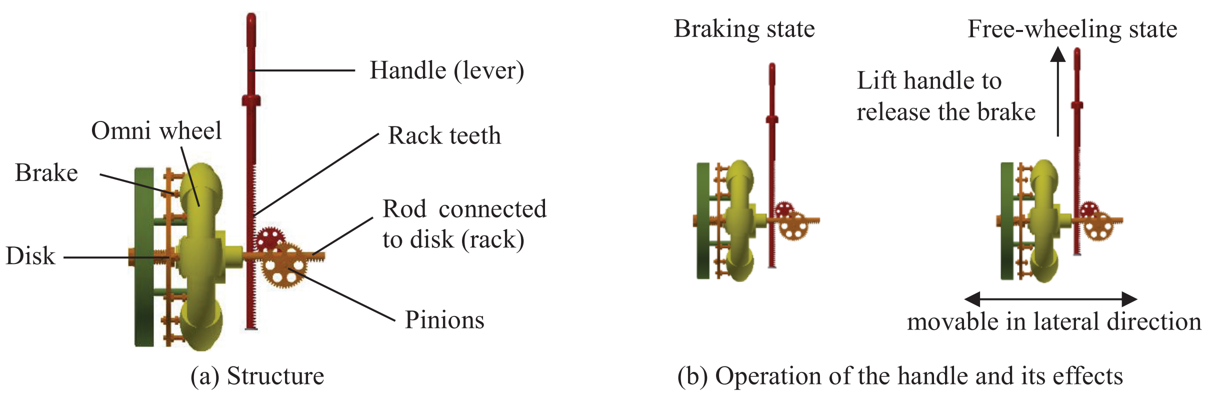

Fig. 7 Operating handle

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2.2.4 Main body

The main body of the proposed vehicle has a chair for the rider to ride and a footrest for the rider's feet. In addition, as mentioned in Section 2.2.2, the main body contains space for installation of the linear guides that move the rear wheels laterally. The front omni wheels are supported by axles connected to the main body.

3. Analysis of space reachable by palms and its impact on operating handle

The proposed vehicle must be designed in consideration of the range of motion of the upper limbs because the vehicle is driven by the upper limbs of the rider. The operation of the linear guides and brakes with the operating handle is specific to the proposed vehicle, and these operations require the rider to move the upper limbs in a way different from that for conventional wheelchairs. This section focuses on the reachable space of the rider's palms and discusses necessary conditions for rider operation of the proposed vehicle with reasonable effort.

3.1 Analysis of reachable space of palms

The rider controls the vehicle's lateral motion by grasping and moving the operating handles in the vertical and lateral directions. Therefore, the handles needed to be designed so as to be operable within the reachable space of the hands. The reachable space of the hands was analyzed numerically first. Note that "palm" and "hand" are regarded as equivalent in this study.

In the simplest model, the reachable space of the palm is a spherical region whose center coincides with the shoulder joint and whose radius is the length of the upper limb. However, the real upper limb of a human can make seven degrees of freedom motion due to the joints of the shoulder, elbow, and wrist, and each joint has a limited range of motion. Such conditions can distort the sphere representing the reachable space and generate unreachable spaces. Based on this idea, the reachable space of the palm was calculated considering the movable range of each joint. In this paper, the posture of the palm is excluded from consideration and the analysis target is the upper right limb.

The coordinate systems corresponding to the joints of the shoulder, elbow, and wrist are set as $\Sigma_1(O_1\text{-}x_1y_1z_1)$, $\Sigma_2(O_2\text{-}x_2y_2z_2)$, and $\Sigma_3(O_3\text{-}x_3y_3z_3)$, respectively, and defined as in Fig. 8. The coordinate system Σ_1 is fixed on the trunk and the origin O_1 coincides with the center of the shoulder joint. Here, the trunk is considered to be constantly upright. At Σ_1, the positive directions of the x_1-axis, y_1-axis, and z_1-axis are the forward, upward, and right directions, respectively. The coordinate system Σ_2 is fixed on the upper arm so that the origin O_2 coincides with the center of the elbow joint. The y_2-axis is on the line passing from the center of the elbow joint to the center of the shoulder joint, and that direction is the positive direction. The z_2-axis is the same as the flexion-extension rotation axis of the elbow, and the positive direction is set so that the elbow flexion direction is positive in a right-handed system. The coordinate system Σ_3 is fixed on the forearm, and its origin O_3 coincides with the center of the wrist joint. The y_3-axis is on the line passing from the center of the wrist joint to that of the elbow joint, and that direction is the positive direction. The x_3-axis is the same as the flexion-extension rotation axis of the wrist, and the positive direction is set so that the wrist flexion direction is positive in a right-handed system. The center of the elbow joint O_2 is located at the position moved in parallel from O_1 by the length of the upper arm along the y_1-axis negative direction and rotated by θ_1 around the z_1-axis, θ_2 around the x_1-axis, and θ_3 around the y_1-axis in that order. The center of the wrist joint O_3 is at the position offset in parallel from O_2 by the length of the forearm along the y_2-axis negative direction and rotated by θ_4 around the z_2-axis and θ_5 around the y_2-axis in that order. Here, let θ_i $(i = 1, 2, \cdots, 7)$ represent the glenohumeral flexion, glenohumeral adduction, glenohumeral external rotation, elbow flexion, elbow pronation, wrist flexion, and wrist abduction, respectively. The movable range of each of θ_i is given as the range of movement of each joint. Table 1 shows the resulting values. In this analysis, each θ_i is considered to change independently from each other.

Displacement of the palm is analyzed by using θ_i. When the homogeneous transformation matrix (Yoshikawa, 1988) is defined as

$$ {}^{i-1}\boldsymbol{T}_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & 0 \\ \sin\theta_i & \cos\theta_i & 0 & -L_{i-1} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{for } i = 1,4,7 $$

$$ {}^{i-1}\boldsymbol{T}_i = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_i & -\sin\theta_i & -L_{i-1} \\ 0 & \sin\theta_i & \cos\theta_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{ for } i = 2,6 \tag{1} $$

$$ {}^{i-1}\boldsymbol{T}_i = \begin{bmatrix} \cos\theta_i & 0 & \sin\theta_i & 0 \\ 0 & 1 & 0 & -L_{i-1} \\ -\sin\theta_i & 0 & \cos\theta_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{ for } i = 3,5 \text{ ,} $$

the homogeneous transformation matrix from the shoulder joint coordinate system to the palm is obtained as follows:

$$ {}^{0}\boldsymbol{T}_7 = {}^{0}\boldsymbol{T}_1\, {}^{1}\boldsymbol{T}_2 \dots {}^{6}\boldsymbol{T}_7 \tag{2} $$

where $L_0 = L_1 = L_3 = L_5 = 0$ and L_2, L_4, and L_6 represent the length of the upper arm, the length of the forearm, and the length from the wrist to the palm, respectively.

From Eqs. (2), the palm position is calculated when the values of L_2, L_4, and L_6 and the joint angles $\{\theta_i\}$ are determined.

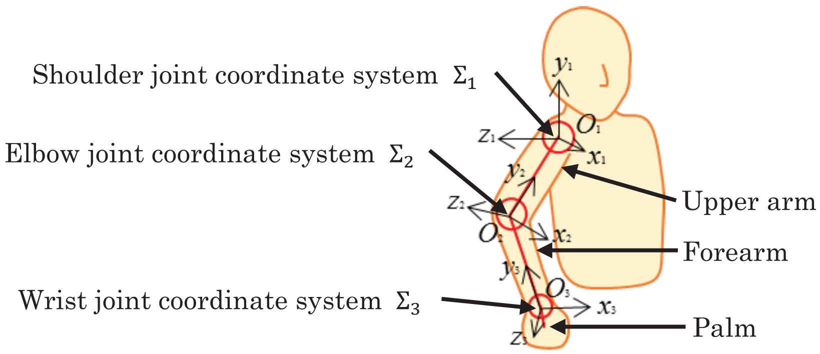

Fig. 8 Coordinate systems to describe movement of the upper limb

Table 1 Joint angles and their ranges of motion

Parameter	Corresponding joint motion	Rotation axis	Range of motion (°) (Kapandji, 2008)
θ_1	Glenohumeral flexion	z_1	$-50 < \theta_1 < 180$
θ_2	Glenohumeral adduction	x_1	$-30 < \theta_2 < 180$
θ_3	Glenohumeral external rotation	y_1	$-110 < \theta_3 < 80$
θ_4	Elbow flexion	z_2	$-5 < \theta_4 < 145$
θ_5	Elbow pronation	y_2	$-85 < \theta_5 < 90$
θ_6	Wrist flexion	x_3	$-85 < \theta_6 < 85$
θ_7	Wrist abduction	z_3	$-55 < \theta_7 < 15$

Figure 9 shows an example of the numerical analysis results of the reachable space of the palm. Here, the limb dimensions are set as $L_2 = 342.0$ mm, $L_4 = 278.0$ mm, and $L_6 = 75.0$ mm, and each axis is normalized by the entire length of the upper limb, that is, $L_2 + L_4 + L_6 = 695.0$ mm. The values of L_2, L_4, and L_6 are 50th percentile values among 217 adult men given from shoulder-elbow length (C10), wall to wrist (C17), and the difference between wall to grip (C18) and wall to wrist (C17), respectively, contained in the Japanese Body Dimension Data (National Institute of Advanced Industrial Science and Technology, 1991). Note that the collisions between the trunk and the upper limb were not checked in this analysis. Figure 9(a) shows that the reachable space of the palm is not spherical but ovoid. Figure 9(b), (c), and (d) shows the y_1z_1 section of the reachable space at $x_1 = -0.5$, 0, and 0.5, respectively. These graphs represent the reachable space in the vertical and lateral directions at each front-back position of the palm. Comparison of Fig. 9(b), (c), and (d) shows that the y_1z_1 section of the reachable space changes as the value of x_1 changes. Figure 9(c) shows that at $x_1 = 0$, the maximum reachable range in the vertical direction and the right direction reaches 1, and the reachable region in $z_1 > 0$ approximately matches a circle whose radius is equivalent to the length of the upper limb. However, the reachable region assumes left-right asymmetry, where the reachable space in $z_1 < 0$ is smaller than that in $z_1 > 0$, especially around $y_1 = 0$, that is, when the palm is at the same height as the

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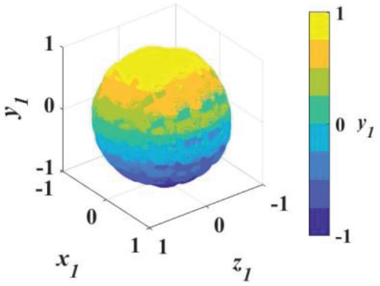
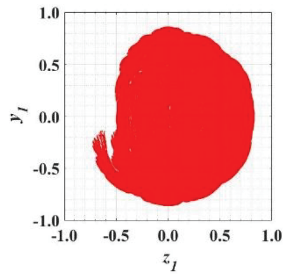
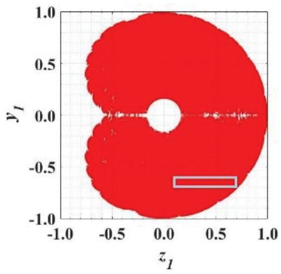
shoulder joint. This might be because the movable range of the shoulder joint is limited when the right palm moves to the range of $z_1 < 0$, that is, to the left side. The graph also shows that there is an area that the palm cannot reach around the origin $y_1 = z_1 = 0$. The origin is equivalent to the center of the shoulder joint. Because the elbow joint needs a large flexion to bring the palm close to the shoulder joint, this unreachable area is considered to be the limit of a fully flexed arm. Comparison of Fig. 9(b) and (d) shows that the reachable region at $x_1 = -0.5$ is smaller than that at $x_1 = 0.5$. The reachable region at $x_1 = 0.5$ almost matches a circle with a radius of 0.8, while there is an unreachable region at $x_1 = -0.5$ in the upper left area, specifically, $-0.5 < y_1$ and $z_1 < -0.5$. This result matches the intuitive understanding that the movable range of the upper limb is limited behind the back.



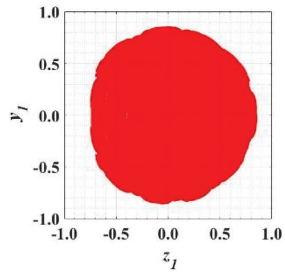
(a) Reachable space of palm



(b) $y_1 z_1$ section of reachable space ($x_1 = -0.5$)



(c) $y_1 z_1$ section of reachable space ($x_1 = 0$)



(d) $y_1 z_1$ section of reachable space ($x_1 = 0.5$)

Fig. 9 Calculation result of the reachable space of the palm

3.2 Design parameters for operating handle

The determined reachable space of the palm (Section 3.1) is used to discuss the design parameters of the operating handles of the proposed vehicle. The functions of the handles are, as stated in Section 2.2.3, to operate the brakes and linear guides. First, the brake operation is discussed. To disengage the brakes, the rider lifts the handle. At this time, the force required to operate the handle depends on the force required to push the brake pads toward the rear wheel. The force to release the brake must be larger than that needed to engage the brakes because a spring keeps the brakes normally engaged. However, it is desirable that the force that the rider needs to apply to lift the handle be as small as possible. Thus, we moderated the force required to lift the handle by using the gear reduction mechanism of the pinions in the brake engagement train. The force to lift the handle decreases when the reduction ratio of the pinions increases. However, an increased reduction ratio increases the operating travel of the handle to pull the brake pads away from the wheel. The reduction ratio used in the prototype was designed in consideration of this trade-off. First, the ratio of manipulation amount of the handle to the entire length of the upper limb was specified to be less than 0.1 according to the reachable range of the palm given in Section 3.1. In addition, considering the burden to the rider, the load to lift the handle was specified to be smaller than 2.0 N. The moving distance required to disengage the brake pads and release the brake was set as 2.0 mm. As a result of the experimental measurement of the pushing force of the brake pads, the force strength required to apply the brake was 40 N. Based on these conditions, the reduction ratio of the pinions was determined as 24:1. In the prototype, the operating travel of the handle was set as 48 mm and the load to lift the handle was approximately 1.7 N, which satisfies the specifications. Because there is backlash in the transmission system between the handle and the brake pads, the actual movable range of the handle is equivalent to the manipulation

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amount of the handle plus the backlash. Thus, in the developed prototype, the movable range of the handle was actually 64 mm.

Next, the linear guide operation is discussed. The linear guides are operated by moving the handles in the lateral direction, as opposed to brake operation in the vertical direction, as described above. These actions correspond to the actions in the z_1 and y_1 directions, respectively, in the shoulder joint coordinate system. As shown in Fig. 10, when the vehicle moves to the left or right, the handle is operated as follows: 1) the handle is lifted vertically to release the brake; 2) the handle is moved horizontally to move the rear wheel to the left or right; 3) the handle is lowered vertically to apply the brake; and 4) the handle is move horizontally to move the main body laterally in the direction opposite to that in Step 2. Therefore, the path of the palm in operating the handle describes a rectangle on the y_1z_1-plane, and the parameters of the vehicle prototype were designed considering the reachable space shown in Fig. 9. Focusing on the lateral direction first, that is, the z_1 direction, when the rider moves the proposed vehicle, the right palm should move in the area of $z_1 \geq 0$ because the palm is likely to interfere with the trunk or the lower limbs in the area of $z_1 < 0$. Therefore, it was decided to use the largest reachable space, that is, the plane of $x_1 = 0$. Next, considering the vertical direction, that is, the y_1 direction. It is desirable that the position of the handles be as close to the wheels as possible because the rider needs to shift the handles and the wheels as necessary. Considering that the height of the shoulder from the seat is 595 mm, which is about 0.86 times as long as the length of the upper limb, according to the 50th percentile value of the suprasternal height, sitting (I7) in the Japanese Body Dimension Data (National Institute of Advanced Industrial Science and Technology, 1991), the area of around $y_1 = -0.7$ was selected. Now, according to the movable range of the handles for brake operation (64 mm), the required movable range of the palm in the y_1 direction is 0.1. This is illustrated in Fig. 9(c) by a light blue rectangle. The reachable range of the palm in the z_1 direction is $0 \leq z_1 \leq 0.7$, but the reachable range may be shorter depending on how the rider grasps the handle because the hand posture is assumed to be arbitrary in the analysis. Furthermore, the entire width of the vehicle becomes large to make the movable range of the linear guides large because they slide within the main body of the vehicle. Considering these factors, the movable range of the linear guides should be smaller than the maximum reachable range of the palm in Fig. 9(c). Based on this analysis, the stroke of the linear guides was set as 304 mm and the movable range as $0.10 \leq z_1 \leq 0.54$.

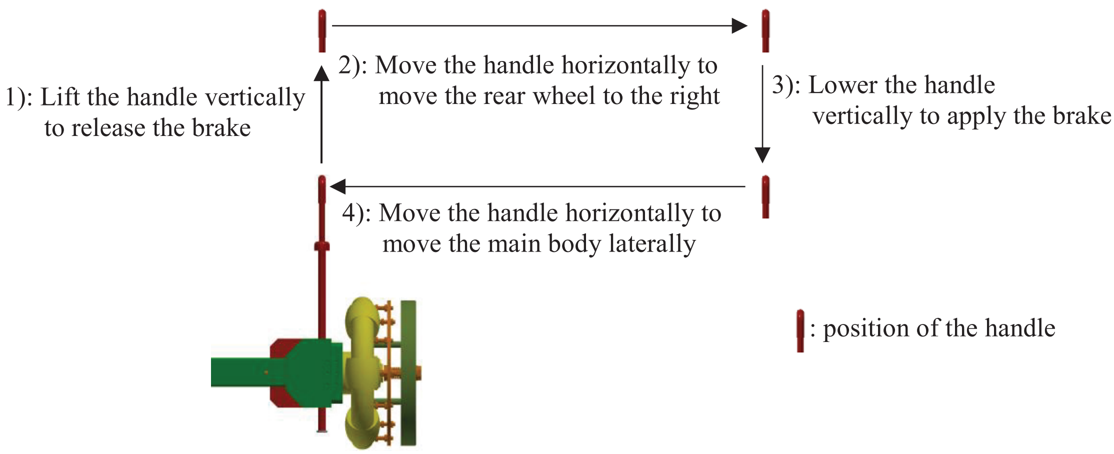

Fig. 10 Manipulation of handle relative to the main body of the vehicle to achieve lateral movement

4. Development of and experiments with vehicle prototype

To verify that the proposed vehicle performs as expected, a vehicle prototype was developed and experiments were performed. The experiments in this paper were conducted with the approval of the Ethics Committee, Graduate School of Engineering, Kyoto University.

4.1 Vehicle prototype

Figure 11 provides an overview of the prototype constructed using the factors discussed in Section 3. The structure

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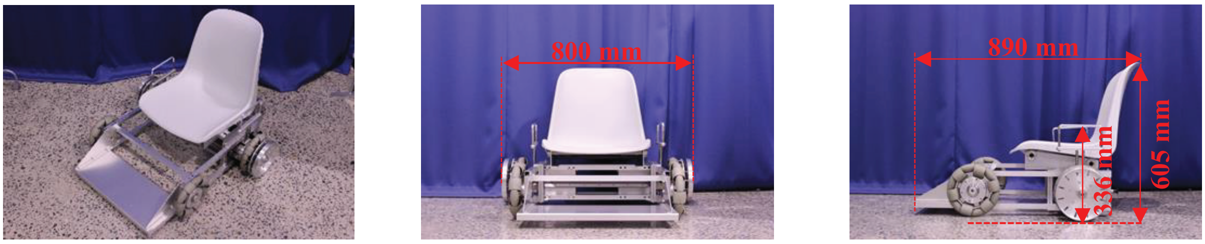
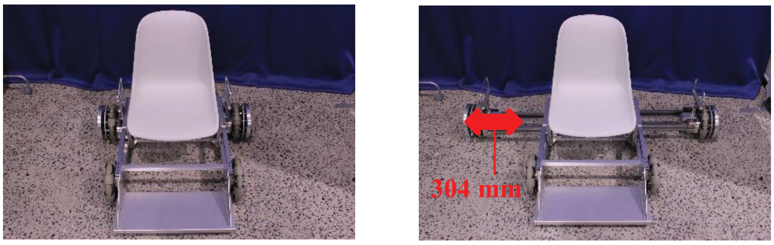
of the vehicle is the same as that explained in Section 2. Figure 12 shows the extension and retraction of the linear guides. The stroke of each of the left and right linear guides is 304 mm. The force required to slide the guide is about 30 N. Figure 13 shows the operation of the rear wheel brakes. The brake is applied while the handle is lowered [Fig. 13(a)]. When the driver lifts the handle up, the brake pads separate from the outer rollers of the wheel, and the brake is disengaged [Fig. 13(b)]. The entire width of the vehicle is 800 mm, the entire length is 890 mm, and the entire height is 605 mm. The height from the ground to the top of the handle is 336 mm when the handle is in the resting position. Table 2 shows basic prototype dimensions.



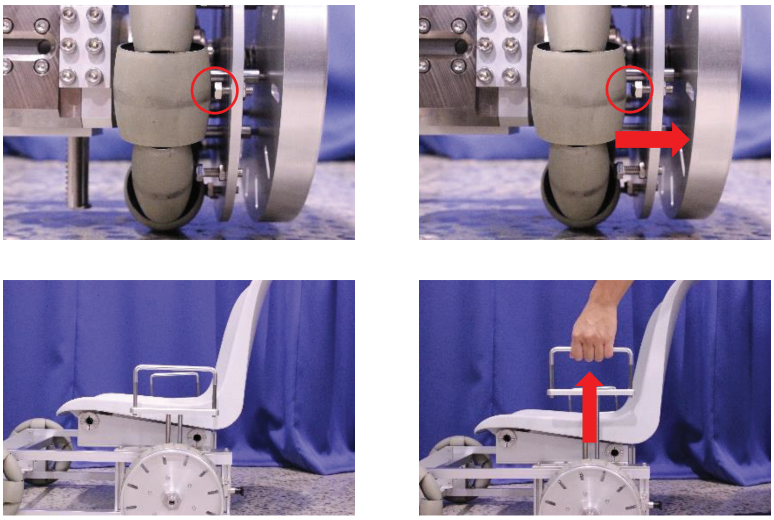
(a) Overall view (b) Front view (c) Side view

Fig. 11 Developed human-powered vehicle prototype



(a) Linear guides retracted (b) Linear Guides extended

Fig. 12 Motion of linear guides in the prototype



(a) Braking (b) Free-wheeling

Fig. 13 Braking mechanism of the prototype

Table 2 Prototype basic dimensions

Distance between front and rear wheels	400 mm
Diameter of omni wheels	200 mm
Height of the seat	205 mm

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4.2 Motion experiment

A motion experiment was carried out to confirm that the developed vehicle operates as expected. Figure 14 shows (a) forward movement, (b) turning, and (c) lateral movement to the right with a rider operating the vehicle. The rider propelled the vehicle forward by rotating the left and right wheels in the same direction at the same velocity, and turned the vehicle by rotating the wheels in the opposite direction at the same velocity. In the right translation, the rider released the right wheel brake, moved the right wheel to the right, applied the right wheel brake, moved the main body to the right, released the left wheel brake, moved the left wheel to the right, and applied the left wheel brake, in that order, in the same way as depicted in Fig. 2. As shown in Fig. 14, it was confirmed that the vehicle was able to move forward and backward, turn, and move laterally as expected. In addition, according to the evaluation of the rider, none of these operations required unreasonable effort during the vertical and lateral operation of the handles with respect to the spatial operating envelope of the arms and the required force.

(a) Forward movement (b) Turning (c) Lateral movement

Fig. 14 Operation of the vehicle prototype

5. Experiment to evaluate the validity of the lateral movement
5.1 Experimental objective and method

When a conventional wheelchair moves in the lateral direction, it turns to change the forward direction first, then moves the intended distance, and finally turns again to return to the initial forward direction. These actions are generally very easy in a sufficiently wide passage, but in a narrow passage, turning is difficult and takes more time. In contrast, the proposed vehicle can move in the lateral direction without turning. This function is expected to be especially useful when the vehicle is operating in a narrow passage. To validate the mechanism's usefulness, we quantified how much the time is reduced by the lateral translation with omni wheels for different passage widths. Then, we examined the effect of the lateral translation on the time needed to perform the operation by comparing both locomotion methods in a narrow passage.

In the experiment, two types of moving methods were observed: One is “translation,” in which the vehicle moves in the lateral direction with omni wheels and linear guides, as shown in Fig. 15(a). The other is “turning,” in which the vehicle moves in the lateral direction by turning at the beginning and end of the maneuver and moving forward (longitudinally) between turns, as shown in Fig. 15(b). The “turning” method is the same as that of a conventional wheelchair.

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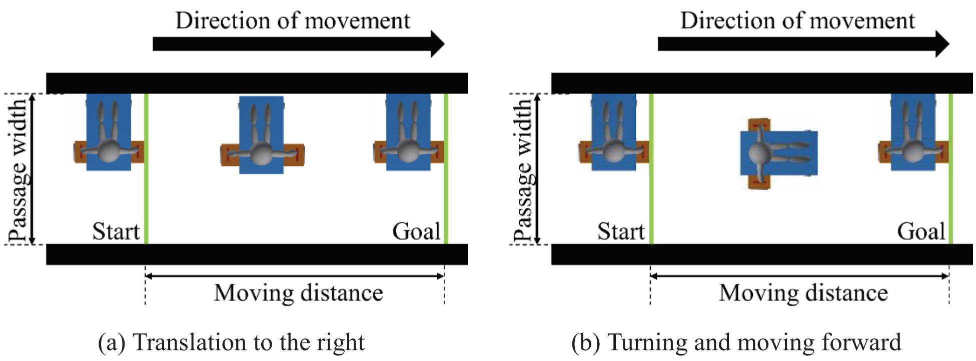

Fig. 15 Two types of motion in the experiment

Nine patterns of experimental environments were used: three passage widths of 1,000 mm, 1,200 mm, and 1,400 mm, and three moving distances of 400 mm, 600 mm, and 800 mm. The narrowest passage width of 1,000 mm is smaller than the length of the diagonal dimension of the vehicle (1,097 mm), so that the vehicle needs to repeat little turns and movements in the longitudinal direction to make a 90° turn. In contrast, the passage width of 1,400 mm is an environment where the vehicle is able to rotate the full 90° in a single turn. In this experiment, it was expected that the difference in passage width would have a large influence on the required time, especially in the "turning" movement, where the vehicle must turn at both the start pointing and goal. In the experiment, walls were placed to mark the passage width limit and tape was applied to the floor as the start and goal lines to delineate the moving distances (Fig. 16). As shown in Fig. 15, initially, the right rear wheel of the vehicle was on the start line and the front edge of the vehicle touched the front wall. Then, the signal for starting the maneuver was given at the same time that the time measurement was started. Measurement stopped when the right rear wheel of the vehicle was on the specified goal line and the front edge of the vehicle touched the front wall at the goal.

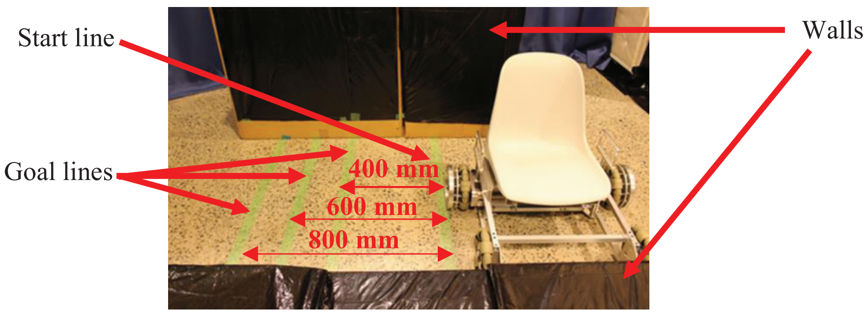

Fig. 16 Experimental layout

In the experiment, the subjects operated the vehicle in the designated space with the two moving methods of "translation" and "turning." The subjects practiced operating the vehicle for 5 minutes to get used to it before the experiment. The subjects were instructed to operate the vehicle within the designated space and position it at the goal with the designated posture "as fast as possible." Table 3 shows the order of the experiment, which was common to all subjects. To compare the required time of "translation" and "turning," the order of the two moving methods was determined at random for each subject. The combination of nine conditions and two moving methods constituted 18 runs in total for each subject, and the lapsed time was measured for each run. The subjects were 10 healthy adults (24.1±1.5 years old) without injury or physical challenge.

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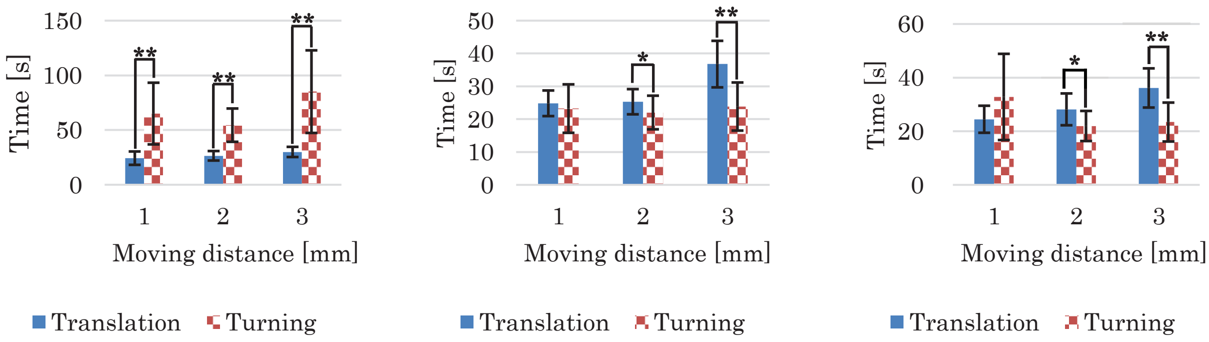
Table 3 Order of experimental operations

Order	Passage width	Moving distance
1st	1,400 mm	400 mm
2nd		600 mm
3rd		800 mm
4th	1,200 mm	400 mm
5th		600 mm
6th		800 mm
7th	1,000 mm	400 mm
8th		600 mm
9th		800 mm

5.2 Experimental results and discussion

First, all 10 subjects succeeded in operating the vehicle without serious troubles and unreasonable efforts. Thus, it was verified that the operation of the vehicle in the lateral movement was sufficiently easy as we had expected.

Figure 17 shows the experimental results. The graphs indicate the average of the required time among all subjects, where the blue bars represent the results of "translation" and the orange bars represent the results of "turning." The whiskers of the plots show 95% reliable sections. The graphs show that the averages of the required time of "translation" are 50% or shorter than those of "turning" in the passage width of 1,000 mm. There are significant differences with the level of significance of less than 1% for all moving distances. In the passage width of 1,200 mm and 1,400 mm, there is no significant difference between the results of "translation" and "turning" in the moving distance of 400 mm. In the moving distance of 600 mm, the averages of the required time of "translation" are about 14.9% longer in the passage width of 1,200 mm and about 28.3% longer in the passage of 1,400 mm than those of "turning," and there are significant differences with the level of significance of 5%. In the moving distance of 800 mm, the averages of the required time of "translation" are about 54.2% and about 54.3% longer than those of "with turning" in the passage widths of 1,200 mm and 1,400 mm, respectively, and there are significant differences with the level of significance of less than 1%. Thus, the effectiveness of "translation" was evaluated quantitatively under every condition.



(a) Passage width 1,000 mm (b) Passage width 1,200 mm (a) Passage width 1,400 mm

Fig. 17 Experimental results (**:p<0.01; *:p<0.05). The p-value means the significant level of Student's t-test.

In the passage width of 1,000 mm, the required time for "translation" is significantly shorter than that for "turning" in all moving distances. This is likely because it was difficult for the vehicle to turn inside a passage 1,000 mm wide. When the vehicle turns with one of the rear wheels fixed, the rotation radius, that is, the distance from the center point of the rotation to the point of the vehicle farthest from it, is about 856 mm and the passage width required for the rotation is about 1,106 mm, as shown in Fig. 18(a). Therefore, it is impossible for the vehicle to rotate a full 90° with one motion in a passage 1,000 mm wide. When the vehicle turns by rotating the left and right wheels in the opposite

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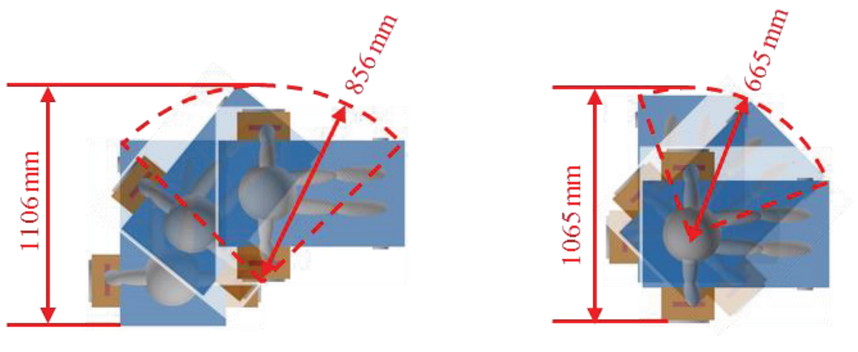
direction, the rotation radius is about 665 mm, as shown in Fig. 18(b), which is smaller than that when turning with a rear wheel fixed, but it is also impossible to turn the full 90° in one motion because the rotation requires a passage width of 1,065 mm. However, it is theoretically possible to turn the full 90° with multiple motions by turning and moving in the longitudinal direction little by little repeatedly. Actually, it was observed that the subjects made a 90° turn by combining turns and longitudinal movements, such as by turning while moving back. Thus, we conclude that the “turning” maneuver takes longer than the “translation” maneuver because vehicle rotation takes more time in a narrow passage.

In the passage widths of 1,200 mm and 1,400 mm, the required time for “turning” is significantly shorter than that for “translation” in the distances of 600 mm and 800 mm. In these passage widths, the time to turn can decrease because the vehicle is able to rotate the full 90° in a single motion by turning with one rear wheel fixed or by rotating the left and right wheels in the opposite direction. Thus, the difference between the required time of “translation” and “turning” tends to be larger as the moving distance increases. This is thought to be because the average of the moving velocity for “translation” is smaller than that for “turning.” The rider basically makes only the operation of the lateral movement for “translation.” However, the vehicle turns and moves forward for “turning.” Considering the operating manner of the vehicle, the velocity of forward motion is likely to be greater than that for lateral translation. It is thought that this is why the difference between the required time for “translation” and “turning” becomes larger as the moving distance increases in the passage widths of 1,200 mm and 1,400 mm.

Based on these factors, we conclude that “translation” provides a favorable transit time when the vehicle moves in a narrow passage or over a short distance, while “turning” is favorable in other cases. Because the proposed vehicle can move by both “translation” and “turning” maneuvers according to the environment or situations, it is expected to move more efficiently overall than a conventional wheelchair that can move only by turning maneuvers.

Here, we examine the threshold for choosing between the two moving methods, in terms of total transit time. With regard to the passage width, “translation” is advantageous when the passage width is 1,000 mm, which is smaller than the passage width required by a vehicle that turns 90° in a single rotation (from 1,056 mm to 1,106 mm). As described above, a time-consuming process combining short forward and turning motions is required when the passage width is smaller. By generalizing this idea, the threshold for choosing the “translation” method is when the passage width is narrower than the passage width required for rotating the vehicle 90° in a single motion. Indeed the wheel size of the vehicle developed in this research is small. The experimental results such as the moving time may change if the wheel diameter or other dimensions of the vehicle are varied. However, the conclusion about the threshold is considered to maintain its generality. Thus, the proposed vehicle has an advantage over the conventional vehicle in terms of moving efficiency in the situation where the passage width is smaller than the diagonal length of the vehicle.



(a) Rotation about one rear wheel (b) Rotation about midpoint of both rear wheels

Fig. 18 Rotation radii of the developed vehicle (90° turn)

6. Conclusion

Human-powered wheelchairs are an important tool of transportation for physically challenged or elderly people, but conventional wheelchairs have the problem of not being capable of moving in a lateral direction. This research aimed to develop a vehicle that can move in both the longitudinal and lateral directions while the rider is powering the

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vehicle by hand. The following results were obtained:

1) Based on the action of a person walking in a lateral direction, we proposed a lateral movement method in which the rider accomplishes the maneuver by repeating vertical and horizontal motions with his or her hands and then constructed a mechanism to realize this method.
2) We analyzed the reachable space of the palm of the rider and clarified that the space became maximum when the palm position in the longitudinal direction was close to the shoulder joint. Based on the analytical result of the reachable space when the palm was located at that point, we clarified the design condition of the operating handles to optimize the palm range of motion required to operate the vehicle with minimal effort.
3) We designed and developed a prototype of the proposed vehicle and conducted experiments. The results confirmed that the developed vehicle was capable of moving in the longitudinal and lateral directions and turning as expected. With respect to the lateral movement of the vehicle, we compared the moving methods where the rider moved the vehicle using the new lateral translation and the conventional method using vehicle rotation in various passage widths and moving distances. The results showed that the proposed lateral movement method was advantageous when the passage width was narrow or the moving distance was short.

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