Munakata and Wada *ROBOMECH Journal* (2015) 2:7
DOI 10.1186/s40648-015-0028-9

ROBOMECH Journal
a SpringerOpen Journal

RESEARCH ARTICLE Open Access

Development and analysis of a novel add-on drive mechanism for motorizing a manual wheelchair and its step climbing strategy

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Abstract

In this study, a novel step climbing method for a five-wheeled wheelchair, composed of a manual wheelchair and an active-caster drive system, has been proposed. Because the active-caster has the same configuration as a passive caster, an arbitrary velocity can be generated by controlling its wheel and steering shafts. Thus, the motion of the proposed wheelchair can be controlled in 2DOF (two degrees of freedom) despite the single-wheel drive system. Moreover, by changing the number of points of contact between the wheelchair and the ground using a linear actuator, two types of motion can be accomplished, similar to front and rear drive modes.
In addition, a novel add-on mechanism, which can perform not only the suggested step climbing method but also the previous functions of the wheelchair, has been proposed. Because the five-wheeled wheelchair has five points of contact with the ground, when the front casters hover above the ground, the wheelchair has adequate stability due to other three wheels contacting the ground to easily perform a "static wheelie" motion. Similarly, the wheelchair can also maintain its stability when the large wheels hover above the ground. The proposed method makes use of this stability to achieve the step climbing of the front casters and large wheels, whereas the drive wheel is lifted onto the step by cooperative control of the linear actuator and drive wheel. By comparing with a step climbing method that uses only the traction force of the drive wheel, the advantages of the proposed method were analyzed. Moreover, the design conditions of the proposed mechanism for realizing the suggested step climbing method were derived. Finally, a prototype was built and experimentally tested to confirm that the wheelchair user can climb over a step using the proposed method and mechanism.

Keywords: Active-caster; Five-wheeled wheelchair; Step climbing

Background

In recent years, the motorized wheelchair, which combines a manual wheelchair and an add-on drive system, has become a popular support system for the elderly. Because it is lightweight and foldable, users can carry it by car with no assistance, expanding their activity areas dramatically. However, users are restricted by obstacles such as steps, stairs, and rough roads, which inhibit the movement of the motorized wheelchair. In the stairs, the wheelchair users can pass over them because many places where there are stairs have another moving method such as elevators and slopes. In contrast, there are many steps in everyday life. In this condition, users are restricted the area to move or they have a risk for falling to backward.

In general, a dual-wheel drive system that propels the two large wheels is used in most motorized wheelchairs (Figure 1(a)) [1]. This system requires the user to get up from the wheelchair when attaching the drive wheels because the large wheels have to be detached. For climbing over a step, some users perform a wheelie motion by hovering the two small front casters. However, because an appropriate electric control device has not been developed for this motion, it has to be performed manually, which requires a sense of balance and has the risk of the user falling backwards. Thus, elderly users with

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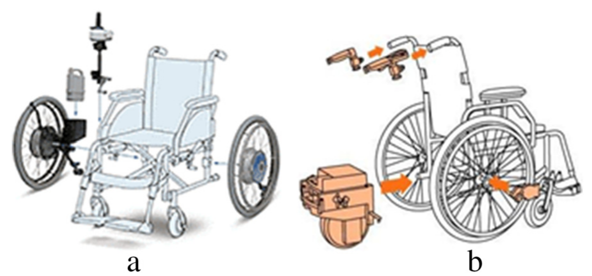

Figure 1 Conventional drive systems for motorizing a manual wheelchair. (a) Dual-wheel drive system. It propels the two large wheels. When the left and right wheels rotate same direction, a wheelchair performs translational motion. When they rotate different direction with same velocities, a wheelchair performs pivot turn motion. **(b)** Single-wheel drive system. When a wheelchair performs translational motion, a drive wheel directs to the back and forth direction. When a wheelchair performs pivot turn motion, a drive wheel directs to the left and right direction. A user has to wait until the direction of it changes.

reduced physical ability cannot use this technique to climb over steps.

To overcome this limitation, a five-wheeled wheelchair composed of a manual wheelchair and a single-wheel drive system has been proposed (Figure 1(b)) [2]. The drive wheel in this system can be attached easily while the user sits in the wheelchair. However, this wheelchair has nonholonomic constraints, thus preventing the user from controlling over motions in 2DOF (two degrees of freedom), namely translational motion and pivot turn motion. To control the two wheelchair motions, the user has to wait until the direction of the drive wheel changes according to the type of motion. A step climbing method for this type of wheelchair has not been considered before.

Previous researches have proposed step climbing methods for wheelchairs using cooperative control with a robot [3] or attached legs [4], but these mechanisms are restricted in their use environment. A system to climb in a diagonal direction by fixing the steering shaft of the front casters [5] has also been suggested, but only the climbing of the front casters has been achieved by this method.

In this study, for expanding the activity area of wheelchair users, a novel step climbing method for a five-wheeled wheelchair has been proposed, and an add-on mechanism for realizing this method by electric operation has been developed. In a previous research by the authors, a five-wheeled wheelchair composed of a manual wheelchair and an active-caster drive system was suggested. The wheelchair with this configuration can perform a stable “static wheelie” motion by hovering the front casters, while the other three wheels contact the ground, and can similarly maintain the stability when the large wheels hover. By making use of these hovering motions, electrically operated step climbing processes for the front casters and large wheels have been recommended. Additionally, a step climbing method for the drive wheel has been proposed. The series of wheelchair motions involved in this step climbing method was analyzed by deriving the kinematics model, and the proposed method was compared with a step climbing method that uses only the traction force of the drive wheel to confirm its advantage. Moreover, the design conditions of the mechanism for realizing the proposed step climbing method were obtained through a simulation analysis and used to construct a prototype. Finally, a motion experiment was performed with the prototype to confirm that the wheelchair can climb over a step by the suggested method.

Proposed five-wheeled wheelchair

In this chapter, the active-caster drive system and the mechanism of the previously suggested five-wheeled wheelchair are described.

A. Active-caster drive system

An active-caster has the same configuration as a passive caster, as shown in Figure 2. The rotational motions of the wheel and steering shafts, ω_w and ω_s, generate active velocities along the wheel rotation and perpendicular directions, V_w and V_s, respectively. By cooperative control of these velocities, the active-caster generates a velocity V_d on the steering shaft with the required direction and magnitude [6].

B. Functions of the five-wheeled wheelchair

A five-wheeled wheelchair proposed since before is composed of a manual wheelchair, a linear actuator and an active-caster drive system shown in Figure 3. It can be attached at the back of the manual wheelchair even

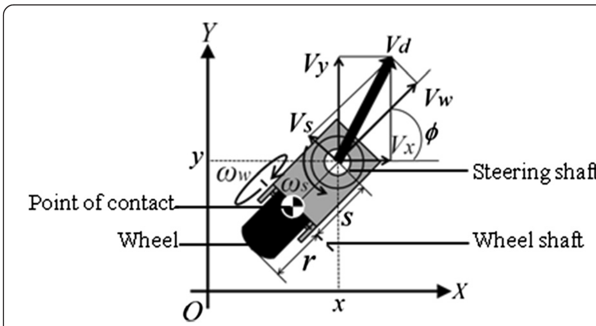

Figure 2 Principle of an active-caster (caster mechanism). It is a same mechanism as a passive caster. The rotational motions of the wheel and steering shafts, ω_w and ω_s, generate active velocities along the wheel rotation and perpendicular directions, V_w and V_s, respectively. By cooperative control of these velocities, the active-caster generates a velocity V_d on the steering shaft with the required direction and magnitude.

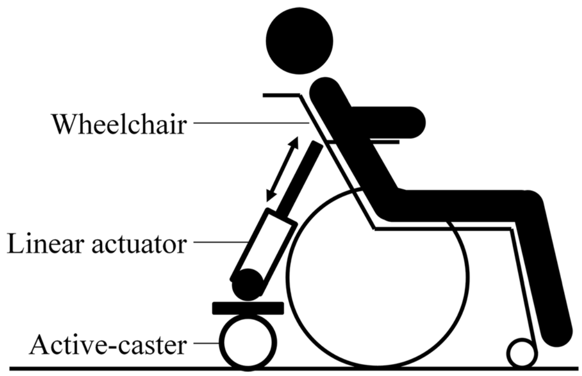

Figure 3 Five-wheeled wheelchair proposed since before. It is composed by a manual wheelchair, a linear actuator and an active-caster drive system. It can be attached at the back of a manual wheelchair even when the user sits in it. By stretching and shrinking motion of the linear actuator, a road distribution of each wheel can be changed. Because of the active-caster, the proposed wheelchair can have independently controlled motions in 2DOF, namely translational motion and pivot turn motion, in spite of the single-wheel drive system.

when the user is sitting in it. By stretching and shrinking motion of the linear actuator, a road distribution of each wheel can be changed. The proposed five-wheeled wheelchair has five points of contact with the ground. Therefore it has more stability than a conventional motorized wheelchair shown in Figure 1(a). In this reason, the proposed wheelchair has no risk to falling. However, in a rough terrain, the driving wheel cannot contact on the ground. In this condition, users cannot move any more. To avoid this situation, some devices such as suspension should be attached to the mechanism. Because of the active-caster, the proposed wheelchair can have independently controlled motions in 2DOF, namely translational motion and pivot turn motion, in spite of the single-wheel drive system. Conventional wheelchairs, which consist of two caster front wheels and two large rear wheels, have only a rear drive mode in which the center of rotation is between the large wheels. In this mode, the user has to perform complex maneuvering to drive through a narrow space. To overcome this difficulty, a novel mechanism has been proposed for the five-wheeled wheelchair so that it can switch between two modes, similar to front drive mode and rear drive mode. This mechanism is realized by a linear actuator, attached between the active-caster and the wheelchair, which can vary the height of the drive wheel to change the number of points of contact with the ground. When all five wheels are in contact with the ground, the wheelchair can perform a pivot turn motion around the center of the large wheels (Figure 4(a)) [7]. Figure 4(a) shows that the large wheels contact on the ground and are rotated since the markers of the large wheels move gradually. On the other hand, when the large wheels are hovered above the ground and the steering shafts of the front casters are fixed, the wheelchair can perform the same motion around the center of the front casters, avoiding the nonholonomic constraint of the large wheels (Figure 4(b)) [7]. Figure 4(b) shows that the large wheels float from the ground since the markers of the large wheels don't move.

Method

In this chapter, the proposed step climbing method and add-on drive mechanism for the five-wheeled wheelchair are explained.

A. Step climbing of a five-wheeled wheelchair

The series of motions of the wheelchair involved in the proposed step climbing method is shown in Figure 5. In this study, the height of the step was assumed as 100 mm.

At first, the wheelchair stops in front of the step (Figure 5(a)) and performs a static wheelie motion by hovering the front casters above the ground (Figure 5 (b)). While keeping the posture of the wheelie motion, the wheelchair performs a translational motion so that the front casters climb over the step (Figure 5(c)). After

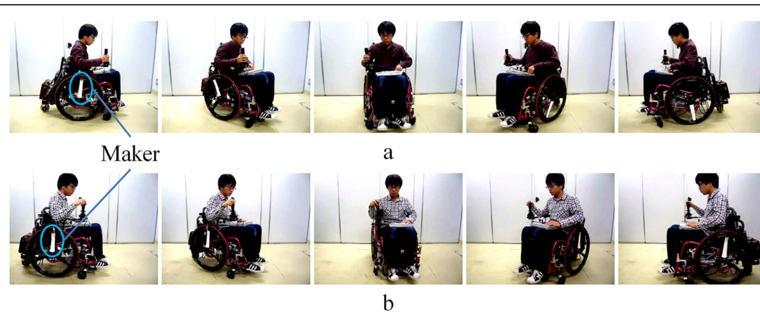

Figure 4 Drive mode change function. (a) Rear drive mode. When all five wheels are in contact with the ground, the wheelchair can perform a pivot turn motion around the center of the large wheels. The large wheels contact on the ground and are rotated since the markers of the large wheels move gradually. **(b)** Front drive mode. When the large wheels are hovered above the ground and the steering shafts of the front casters are fixed, the wheelchair can perform the same motion around the center of the front casters, avoiding the nonholonomic constraint of the large wheels. The large wheels float from the ground since the markers of the large wheels don't move.

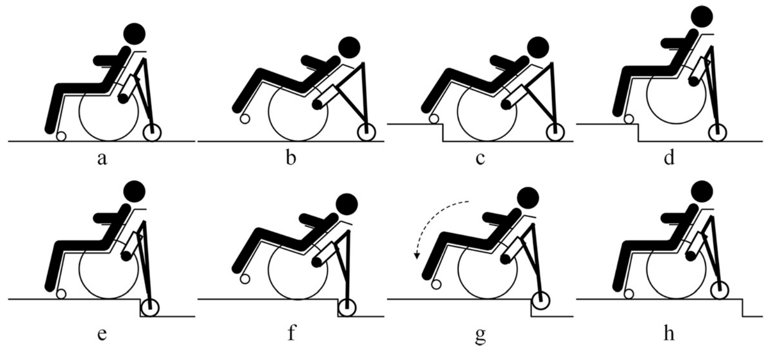

Figure 5 A series of wheelchair motion as the proposed step climbing method. **(a)** The wheelchair stops in front of the step. **(b)** The wheelchair performs a static wheelie motion by hovering the front casters above the ground. **(c)** While keeping the posture of the wheelie motion, the wheelchair performs a translational motion so that the front casters climb over the step. **(d)** After the front casters climb, the large wheels are made to hover above the ground by changing the height of the drive wheel. **(e)** The large wheels pass over the step by a translational motion. **(f)** After the large wheels climb, the wheelchair performs a static wheelie motion on the step. **(g)** By cooperative control of the drive wheel and the linear actuator, the front casters land at the same time that the drive wheel climbs on the step. **(h)** the wheelchair moves on the step.

the front casters climb, the large wheels are made to hover above the ground by changing the height of the drive wheel (Figure 5(d)), and then they pass over the step by a translational motion (Figure 5(e)). After the large wheels climb, the wheelchair performs a static wheelie motion on the step (Figure 5(f)), and the brakes of the large wheels are locked. By cooperative control of the drive wheel and the linear actuator, the front casters land at the same time that the drive wheel climbs on the step (Figure 5(g)). Finally, the wheelchair moves on the step (Figure 5(h)) by translational motion. In the following section, the mechanism to realize this proposed step climbing method is introduced. The step climbing method is divided into three processes, namely the climbing processes of the front casters (Figure 5(a)–(c)), the large wheels (Figure 5(d),(e)), and the drive wheel (Figure 5(f)–(h)). For each of these processes, the proposed step climbing method is compared with a method that uses only the traction force of the drive wheel, in order to confirm its advantage. Finally, the design conditions of the mechanism required to realize the proposed step climbing method are derived.

B. A novel add-on drive mechanism

In the five-wheeled wheelchair proposed since before, the front casters and the active-caster cannot hover from the ground by only the traction force of the linear actuator. To overcome this problem, we proposed the step climbing method of the front casters in our recent research. After replacing the linear actuator with the links, by connecting with pin joint between the links and the frames of the wheelchair, the wheelchair performed a static wheelie motion and the front casters were hovered from the ground [8]. By combining this step climbing method of the front casters and the float system of the large wheels shown in Figure 3, we propose the step climbing method of the five-wheeled wheelchair. The proposed step climbing mechanism, which is composed of a linear actuator, an active-caster, and some frames, is shown in Figure 6. Point A is at the top of the linear actuator, and point B is on its frame. Points C and D are on the wheel shaft of the active-caster and on the frame AC, respectively. The linear actuator is attached at the back of the wheelchair frame at an angle α, and the points A, B, and D are connected with pin joints so that they can be rotated. The maximum value of the angle β (∠BAD) is restricted by the length of the link BD. By cooperative control of the linear actuator and the active-caster, the points C and D can be moved. When the length of the linear actuator u_L is varied, the angle β between the frame AD and linear actuator AB and the

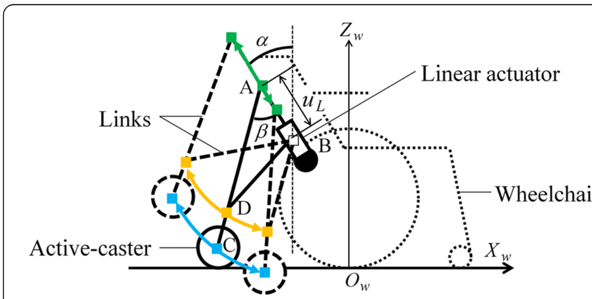

Figure 6 Concept of the proposed step climbing mechanism. It is composed of a linear actuator, an active-caster, and some frames. Point A is at the top of the linear actuator, and point B is on its frame. Points C and D are on the wheel shaft of the active-caster and on the frame AC, respectively. The linear actuator is attached at the back of the wheelchair frame at an angle α, and the points A, B, and D are connected with pin joints so that they can be rotated. The maximum value of the angle β (∠BAD) is restricted by the length of the link BD. By cooperative control of the linear actuator and the active-caster, the points C and D can be moved.

coordinates of the points A, C, and D can be represented by the following equations:

$$\cos\beta = \frac{u_L^2 + l_1^2 - l_2^2}{2u_L l_1} \tag{1}$$

$$\begin{bmatrix} x_a \\ z_a \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} 0 \\ u_L \end{bmatrix} + \begin{bmatrix} x_b \\ z_b \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} x_c \\ z_c \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} -l_0 \sin\beta \\ u_L - l_0 \cos\beta \end{bmatrix} + \begin{bmatrix} x_b \\ z_b \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} x_d \\ z_d \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} -l_1 \sin\beta \\ u_L - l_1 \cos\beta \end{bmatrix} + \begin{bmatrix} x_b \\ z_b \end{bmatrix} \tag{4}$$

where $x_{\{a,\ b,\ c,\ d\}}$ and $z_{\{a,\ b,\ c,\ d\}}$ are the coordinates of the positions A, B, C, and D, respectively, and $l_{\{0,\ 1,\ 2\}}$ are the length of the links AC, AD, and BD, respectively.

As the proposed step climbing method, the drive wheel moves to the backward direction when the wheelchair performs a wheelie motion (Figure 5(b)), while the linear actuator shrinks for lowering the height of the drive wheel during the hovering motion of the large wheels (Figure 5(d)). The maximum value of the angle is calculated by the differential of the equation (1).

$$\frac{d(\cos\beta)}{du_L} = \frac{l_2^2 + u_L^2 - l_1^2}{2u_L^2 l_1} \tag{5}$$

Here, if $l_1 \leq l_2$, the wheelchair cannot keep the posture of the static wheelie motion because the value of the angle has no limit. On the other hand, if $l_1 > l_2$, the wheelchair can keep the posture of the static wheelie motion at the maximum value of the angle. Therefore in the equation (5), the step climbing method is realized by the proposed mechanism when the condition $l_1 > l_2$ is satisfied.

C. Analysis of the step climbing of the front casters

To confirm the advantage of the proposed method, the step climbing process of the front casters (Figure 5(a)–(c)) is analyzed by considering three methods:

- A method that uses only the traction force of the drive wheel.
- A method in which the wheelchair performs a wheelie motion without brakes.
- A method in which the wheelchair performs a wheelie motion with brakes.

For the method that uses only the traction force of the drive wheel, the kinematics model of a wheel climbing over a step is shown in Figure 7. The condition required for the front casters to climb over the step is represented by the equation:

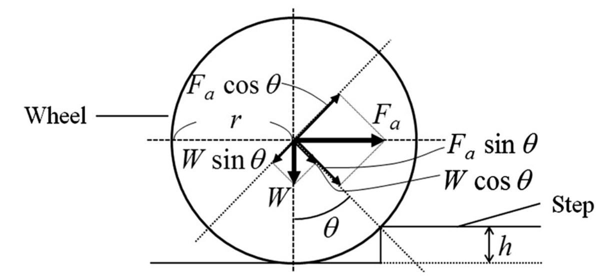

Figure 7 Step climbing model of a wheel. Front and large wheels cannot generate drive force in the proposed five-wheeled wheelchair. When these wheels climb over a step, the drive wheel propels from the backwards.

$$F_a \cos\theta \geq 2W \sin\theta \tag{6}$$

where F_a is the traction force of the drive wheel, θ is the angle between the vertical direction and the point of contact on the step, and W is the vertical load of the wheel.

To satisfy equation (6), the angle θ, represented in terms of radius of the wheel r and height of the step h, has to satisfy the following condition:

$$\cos\theta = \frac{r-h}{r} \geq 0 \tag{7}$$

In general, the radius of the front casters of a wheelchair is between 50 mm and 100 mm. Equation (7) cannot be satisfied by these dimensions, and thus the front casters cannot climb over a step using only the traction force of the drive wheel.

Next, we analyze two step climbing methods which use the proposed mechanism. When the wheelchair performs a static wheelie motion, there is a possibility that the active-caster slips on the ground. In the following, we confirm the traction force of the drive wheel at the wheelie motion of the wheelchair.

For the method that uses the static wheelie motion of the proposed step climbing mechanism without brakes in the large wheels, the motion of the wheelchair frame is shown in Figure 8(a). When the brakes are not used, the wheelchair frame rotates about the wheel shafts of the large wheels. By the principle of virtual work, the traction force required to perform the static wheelie motion is represented by the equation:

$$F_a = \frac{Mg \cdot \delta z_g}{\delta L_c} \tag{8}$$

where M is the total weight of the wheelchair frame and user, g is the gravitational acceleration,

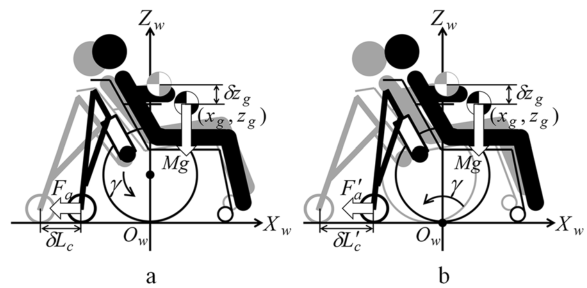

Figure 8 Wheelie motion of the wheelchair. (a) Without brakes. When the brakes are not used, the wheelchair frame rotates about the wheel shafts of the large wheels. **(b)** With brakes. When the brakes are used, the wheelchair frame rotates about the point of contact with the ground. This is a combined motion in which the wheelchair frame rotates about the wheel shafts of the large wheels while the large wheels rotate in the backwards direction.

and δz_g and δL_c are the infinitesimal displacements of the center of gravity of the wheelchair and the drive wheel, respectively. δz_g and δL_c are given by the following equations:

$$\delta z_g = L_g \cos(\alpha_g + \gamma) \cdot \delta\gamma \tag{9}$$

$$\delta L_c = \sqrt{\left(\frac{\delta x_c}{\delta\beta}\right)^2 + \left(\frac{\delta z_c}{\delta\beta}\right)^2} \cdot \delta\beta \tag{10}$$

where L_g is the length between the wheel shaft of the large wheels and the center of gravity, α_g is the angle between the X_w axis and the center of gravity, γ is the inclining angle of the wheelchair, and δx_c and δz_c are the infinitesimal displacements of x_c and z_c from equation (3), respectively. By using the relation between the infinitesimal angles δγ and δβ, the traction force required to perform the static wheelie motion can be calculated by equations (8), (9), and (10).

For the method that uses the static wheelie motion by the proposed mechanism with brakes in the large wheels, the motion of the wheelchair frame is shown in Figure 8(b). When the brakes are used, the wheelchair frame rotates about the point of contact with the ground. This is a combined motion in which the wheelchair frame rotates about the wheel shafts of the large wheels while the large wheels rotate in the backwards direction. By the principle of virtual work, the traction force required to perform the static wheelie motion F'_a is represented by the equation:

$$F'_a = \frac{Mg \cdot \delta z_g}{\delta L'_c} \tag{11}$$

$$\delta L'_c = \sqrt{\left(\frac{\delta x_c}{\delta\beta} - R\right)^2 + \left(\frac{\delta z_c}{\delta\beta}\right)^2} \cdot \delta\beta \tag{12}$$

where L'_c is the infinitesimal displacement of the drive wheel taking into account the rotation of the large wheels, and R is the radius of the large wheels. By using the relation between the infinitesimal angles δγ and δβ, the traction force required for performing the wheelie motion can be calculated by equations (9), (11) and (12).

Figure 9 shows the relation between the inclination angle of the wheelchair frame and the traction force of the drive wheel required to perform the static wheelie motion, which were obtained from calculations using equations (8) and (11) and the parameters in Table 1. It can be seen from the figure that the required traction force is smaller for the method with brakes and is highest when the front casters hover. Although a smaller traction force is required for the wheelie motion with brakes, complex operations have to be performed by the user to control the brakes of the large wheel. Therefore, in this study, it was ensured that the proposed wheelchair could climb a step by performing the wheelie motion without the brakes of the large wheels.

D. Analysis of the step climbing of the large wheels

To confirm that the proposed step climbing method is better in terms of the step climbing of the large wheels, it is compared with the method that uses only the traction force of the drive wheel.

As mentioned in the previous section, the kinematics model of a wheel climbing over a step is shown in Figure 7, and the condition required for the wheel to climb the step with only the traction force of the drive wheel is represented by equations (6) and (7). When the large wheels climb over the step, the drive wheel has the risk of slipping

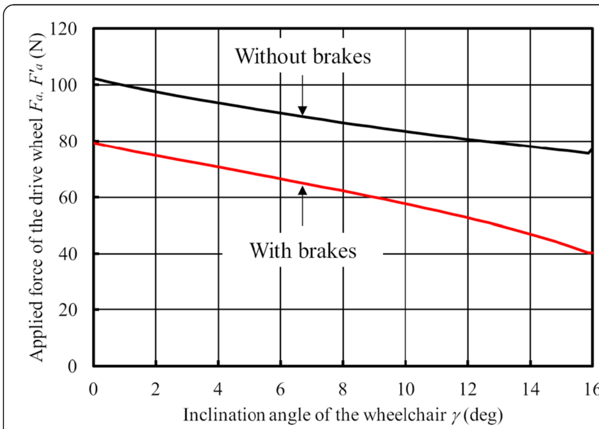

Figure 9 Variation of the traction force in the wheelie motion. It can be seen from the figure that the required traction force is smaller for the method with brakes and is highest when the front casters hover.

Table 1 Parameters of the mechanism and the wheelchair

	Symbol	Value	Unit
Length of the links	l_0	0.75	m
	l_1	0.5	m
	l_2	0.34	m
Attachement positions	α	8	deg
	x_b	-0.14	m
	z_b	0.54	m
Center of gravity	M	85	kg
	x_g	0.099	m
	z_g	0.55	m

on the ground. To avoid this situation, the traction force has to satisfy an additional equation:

$$F_a \leq \mu N \tag{13}$$

where μ is the friction coefficient between the drive wheel and the ground, and N is the vertical load of the drive wheel.

Therefore, from equations (6) and (13), a large wheel of vertical load W_2 can climb over a step using only the traction force if the following condition is satisfied:

$$\theta \leq \tan^{-1}\left(\frac{\mu N}{2W_2}\right) = 12(\deg) \tag{14}$$

From equation (14), it can be seen that the step climbing of the large wheels by only the traction force is affected by the road condition and the load distribution of the wheelchair.

In the proposed step climbing method, the large wheels hover above the ground by adjusting the height of the drive wheel using the linear actuator, and this mechanism was confirmed in a previous study while a user sat on the wheelchair. In this process, the traction force of the drive wheel is not needed, and thus factors such as road condition and load distribution do not affect this method. With the large wheels hovering above the ground, the wheelchair can perform a stable translational motion by fixing the steering shaft of the front casters along the wheelchair frame. Thus, the advantage of the hovering method of the large wheels to climb the step, over the method that uses only the traction force, is confirmed.

E. Analysis of the step climbing of the active-caster

As in section D, the two methods for climbing over a step are compared to analyze the climbing process of the active-caster.

For the method that uses only the traction force of the drive wheel, it is assumed that the drive wheel can perform up-and-down motion without attaching the proposed mechanism. The wheel radius of the active-caster is assumed as 65 mm, and the height of the step is 100 mm, as previously mentioned. In this method, the drive wheel climbs along to the side of the step, but a force is required to make the drive wheel contact the side of the step in order to generate the traction force. However, generating this force for contact is difficult without the proposed mechanism. Thus, the drive wheel cannot climb over a step higher than its wheel radius by the method that uses only the traction force.

In the proposed method using cooperative control of the drive wheel and the linear actuator, the linear actuator stretches to lift the drive wheel onto the step. However, in this motion, the drive wheel could move backwards and lose contact with the side of the step, and the user would not be able to control this by electric operation. To avoid this situation, the wheelchair first performs a static wheelie motion on the step to hover the front casters above the ground in advance. By cooperative control of the shrinking motion of the linear actuator and the traction force of the drive wheel, the drive wheel then climbs onto the step at the same time that the front casters land on the step. Thus, using this proposed method, the drive wheel can climb over a step without relying on the wheel radius. This advantage was also confirmed by an experiment in which the drive wheel climbed over a step higher than its wheel radius.

F. Simulation of the proposed step climbing

In the previous sections, the advantage of the step climbing method by the proposed mechanism was confirmed. In this section, the design conditions of the mechanism for realizing the proposed method are derived. As previously described, in the proposed step climbing method, the front casters hover above the ground by a static wheelie motion, the large wheels hover above the ground by the action of the linear actuator, and the drive wheel climbs the step by cooperative control of the linear actuator and the drive wheel. The design conditions required for the proposed mechanism to perform each of these step climbing processes were investigated through a simulation.

The parameters used in the simulation are shown in Table 1. The wheelchair was initially assumed to be on the ground with five contacting wheels, and the tracks of the points A, C, and D with the variation of the actuator length u_L were calculated using equations (2), (3), and (4), respectively.

The simulation results are shown in Figure 10, in which the large wheel and the front caster are shown to clarify the position of the wheelchair on the ground, shown as G_{ground}. In this simulation, the condition $l_1 > l_2$,

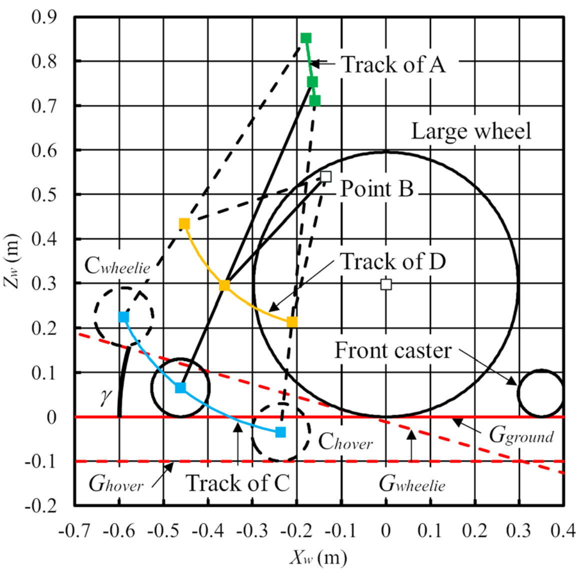

Figure 10 Simulation results (motion of the mechanism). When the wheel shaft moves to the position $C_{wheelie}$ by the proposed mechanism, the line tangential to the large wheels and the drive wheel is defined as $G_{wheelie}$. When the large wheels hover above the ground, the front casters are on the step and the drive wheel is on the ground below the step.

derived in section B, was satisfied by the design parameters.

First, the design condition for the mechanism required for the front casters to climb the step was analyzed. The inclination angle of the wheelchair for climbing over a step of height 100 mm is represented by the following equation:

$$\gamma_{wheelie} = \tan^{-1}\left(\frac{h}{l_f}\right) = 16(\text{ deg}) \tag{15}$$

where $\gamma_{wheelie}$ is the required inclination angle when the front casters climb the step, and l_f is the length between the point of contact of the large wheels with the ground and the point of contact of the front casters with the ground.

When the wheel shaft moves to the point $C_{wheelie}$ by the proposed mechanism, the line tangential to the large wheels and the drive wheel is defined as $G_{wheelie}$. By inclining the wheelchair frame to superimpose $G_{wheelie}$ and G_{ground}, the wheelchair can perform the wheelie motion. In this situation, the angle γ between $G_{wheelie}$ and G_{ground} is the angle that the wheelchair can incline, and when γ exceeds the angle calculated by equation (15), the front casters can climb over the step by the proposed method. From the simulation results, it was established that the front casters can climb over the step if the length of the linear actuator u_L is over 340 mm.

Next, the design condition required for the large wheels to climb the step was analyzed. When the large wheels hover above the ground, the front casters are on the step and the drive wheel is on the ground below the step. Assuming that G_{ground} is the surface of the step, the front casters and the large wheels are at the same height as the step. When the drive wheel moves to the point C_{hover}, it contacts the line G_{hover}, which is defined as the surface of the ground below the step. In this condition, the large wheels hover and can pass over the step by translational motion. When the drive wheel moves to this position, it was evaluated that the length of the linear actuator is 190 mm.

Finally, the design condition required for the drive wheel to climb the step was analyzed. As previously described, for the drive wheel to climb over the step, the wheelchair has to first perform a wheelie motion, for which the design condition has already been obtained. Therefore, by satisfying the same condition, the drive wheel can also climb the step.

Thus, the simulation analysis confirmed that the wheelchair can climb over the step by the proposed method if the mechanism is constructed according to the parameters in Table 1 with a linear actuator whose stroke is over 150 mm. In this paper, we analyze the method for climbing over a step of the height of 100 mm. By changing the length of the links shown Table 1 and analyzing the same investigation, the proposed wheelchair can climb over a higher step.

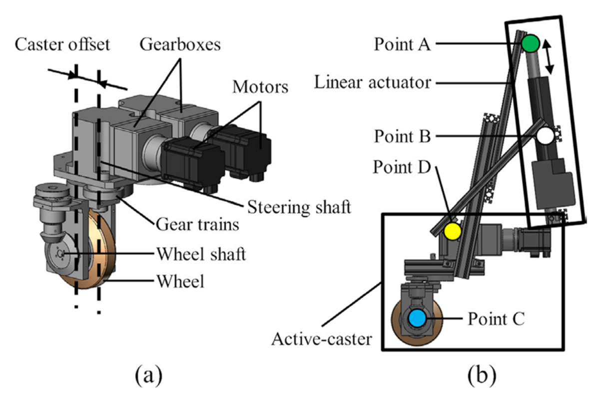

Figure 11 Active-caster drive system and add-on drive mechanism. **(a)** Active-caster drive mechanism. The power from the motors is transmitted via gearboxes and gear trains to the wheel and steering shafts in order to generate the required velocity. To detect the wheel orientation φ, an absolute encoder was attached to the steering shaft. **(b)** A novel add-on drive mechanism. To satisfy the simulation results, a linear actuator with a 200 mm stroke was used, and the length of each link were the same as those listed in Table 1. By attaching this drive mechanism, the wheelchair could be electrically operated.

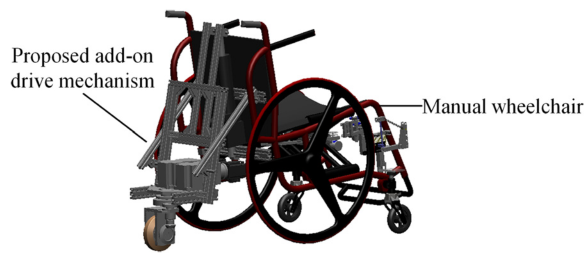

Figure 12 Proposed five-wheeled wheelchair. To construct the prototype, a manual wheelchair (Model: NEO, manufactured by OX Engineering, Co., Ltd.) was used, and the proposed mechanism was attached at the back.

Prototype

The active-caster drive system used in the prototype is shown in Figure 11(a). The power from the motors is transmitted via gearboxes and gear trains to the wheel and steering shafts in order to generate the required velocity. To detect the wheel orientation ϕ, an absolute encoder was attached to the steering shaft. The wheel radius and caster offset used for this prototype were 65 mm and 45 mm, respectively.

The proposed add-on drive mechanism is shown in Figure 11(b). To satisfy the simulation results, a linear actuator with a 200 mm stroke was used, and the length of each link were the same as those listed in Table 1. By attaching this drive mechanism, the wheelchair could be electrically operated, and the stretching and shrinking of the linear actuator could be controlled by the user with a switch.

An illustration of the prototype with the proposed mechanism installed is shown in Figure 12. To construct the prototype, a manual wheelchair (Model: NEO, manufactured by OX Engineering, Co., Ltd.) was used, and the proposed mechanism was attached at the back. Systems for locking the rotational motion of the large wheels (Figure 13(a)) and the steering shaft of the front casters (Figure 13(b)) were also installed. The large wheels could be locked by pulling the toggle brake with a wire, and the front casters could be locked by pulling the pin with a wire. These mechanisms could be controlled by the user with a switch, and were used in the step climbing process as well as in changing the drive mode.

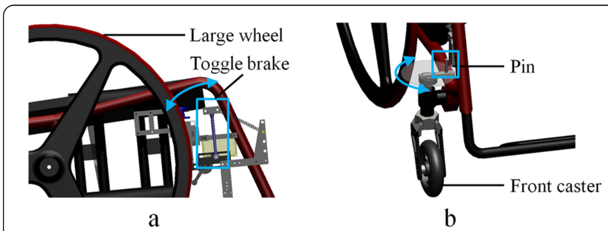

Figure 13 Wheelchair brake systems. (a) Large wheel brake mechanism. The large wheels could be locked by pulling the toggle brake with a wire. **(b)** Caster locking mechanism. The front casters could be locked by pulling the pin with a wire.

Results and discussion

A. Comparison between simulations and experiments

To verify that the prototype satisfied the design conditions for realizing the proposed step climbing method, the motion of the mechanism was tested and compared with the simulation results shown in Figure 10.

In the experiment, the height of the step was assumed as 100 mm, just as in the simulation. As previously described, in the step climbing process of the front casters, the wheelchair performs a static wheelie motion so that the front casters hover above the ground. In the step climbing process of the large wheels, the large wheels hover above the ground until they are at the same height as the step, and in the step climbing process of the drive wheel, the drive wheel climbs along the side of the step by cooperative control of the linear actuator and the drive wheel. The experiment investigated whether the wheelchair could perform these step climbing processes using the constructed mechanism.

The wheelchair was placed on the step with the brakes locked, and the tracks of the points A, C, and D were measured by stretching and shrinking the linear actuator.

The experimental and simulation results were superimposed, as shown in Figure 14. When the linear actuator was stretched, the active-caster moved to the position $C_{wheelie}$, so that the front casters could hover above the

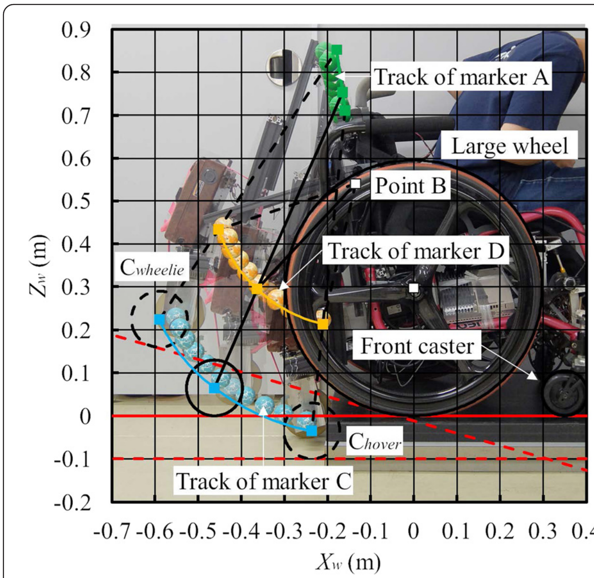

Figure 14 Experimental results of the mechanism. When the linear actuator was stretched, the active-caster moved to the point $C_{wheelie}$, so that the front casters could hover above the ground at the height of 100 mm. In contrast, when the linear actuator was shrunk, the active-caster moved to the point C_{hover} and contacted the ground.

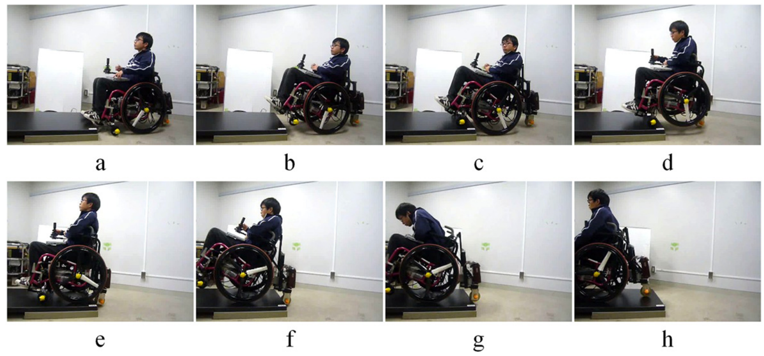

Figure 15 Experimental results (snapshots of a series of motions). (a) The wheelchair stopped in front of the step without brakes **(b)** A static wheelie motion was performed. **(c)** While the front casters hovered, the wheelchair performed a translational motion so that the front casters could climb over the step. **(d)** After the front casters climbed the step, the large wheels were made to hover above the ground at a height of 100 mm by cooperative control of the linear actuator and the active-caster. **(e)** By performing a translational motion, the large wheels climbed over the step. **(f)** By stretching the linear actuator, the wheelchair performed a static wheelie motion on the step. After that, for approaching the drive wheel to the step, the wheelchair performed a translational motion. **(g)** After the brakes of the large wheels were locked, the front casters landed at the same time that the active-caster climbed onto the step by cooperative control of the drive wheel and the linear actuator. **(h)** By performing a translational motion, the wheelchair moved on the step.

ground at the height of 100 mm. In contrast, when the linear actuator was shrunk, the active-caster moved to the point C_{hover} and contacted the ground. Although the experimental results had measurement errors, the tracks of markers A, C, and D were almost the same as in the simulation results, confirming that the prototype could perform the proposed step climbing method.

B. Motion experiment by the proposed method

A motion experiment was conducted to verify that the wheelchair could climb over a step of height 100 mm by the proposed method. The user of the wheelchair was a non-handicapped person. In the experiment, the front casters were locked and the wheelchair steps in front of the step in advance.

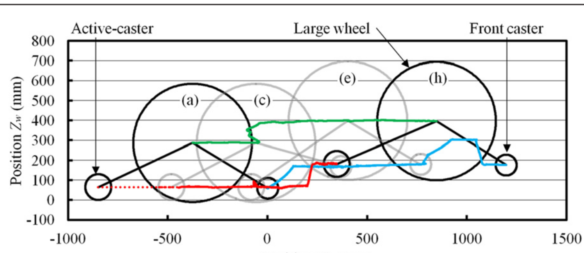

Figure 16 Experimental results (measurement of Quick MAG). We measured tracks of the wheels of the wheelchair with Quick MAG IV type II (OKK Inc.). Three tracks, the front caster, the large wheel, and the drive wheel, are shown in this figure. The position of the front caster when the experiment started is 0mm and the wheelchair motion, (a), (c), (e) and (h), are shown in this figure. The track of the active-caster uses the estimated value between (a) and (c), because it is out of the area which the device can measure.

The experimental results are shown in Figure 15. First, the wheelchair stopped in front of the step without brakes (Figure 15(a)), and then a static wheelie motion was performed (Figure 15(b)), confirming that the wheelchair prototype could perform the wheelie motion without brakes. While the front casters hovered, the wheelchair performed a translational motion so that the front casters could climb over the step (Figure 15(c)). After the front casters climbed the step, the large wheels were made to hover above the ground at a height of 100 mm by cooperative control of the linear actuator and the active-caster (Figure 15(d)). Then, by performing a translational motion, the large wheels climbed over the step (Figure 15(e)). Next, by stretching the linear actuator, the wheelchair performed a static wheelie motion on the step. After that, for approaching the drive wheel to the step, the wheelchair performed a

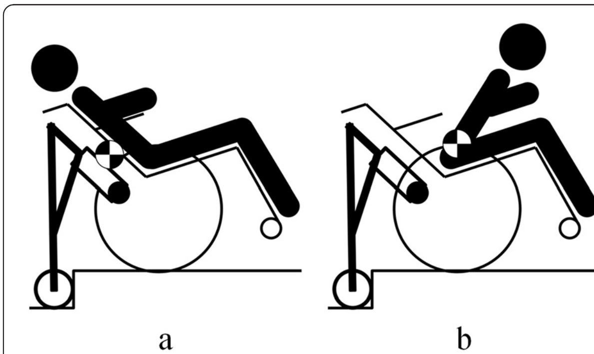

Figure 17 Movement of center of gravity. (a) The center of gravity is on the back of the wheelchair. **(b)** By changing the posture of the user, the center of gravity moves to the forward direction.

translational motion (Figure 15(f)). After the brakes of the large wheels were locked, the front casters landed at the same time that the active-caster climbed onto the step by cooperative control of the drive wheel and the linear actuator (Figure 15(g)). Finally, by performing a translational motion, the wheelchair moved on the step (Figure 15(h)).

In this experiment, we measured tracks of the wheels of the wheelchair with Quick MAG IV type II (OKK Inc.) in addition to measuring a video camera shown in Figure 15. The measurement results are shown in Figure 16. Three tracks, the front caster, the large wheel, and the drive wheel, are shown in this figure. Two front casters and large wheels are attached on the wheelchair. However, we measured one wheel respectively because the wheelchair is symmetry. The position of the front caster when the experiment started is 0 mm and the wheelchair motion, (a), (c), (e), and (h), are shown in this figure. The track of the active-caster uses the estimated value between (a) and (c), because it is out of the area which the device can measure. In this figure, we confirmed that each wheel moved continuously and changes the position Z_w about 100 mm. Therefore we confirmed the proposed wheelchair could pass over a step which height was 100 mm [see Additional file 1].

In this experiment, the motion which moves center of gravity was needed when the active-caster passed over a step (Figure 15(f)-(h)). This motion is shown in Figure 17. In Figure 15(f), the center of gravity is on the back of the wheelchair shown in Figure 17(a). By changing the posture of the user, the center of gravity moves to the forward direction shown in Figure 17(b). Assuming that the wheelchair frame is the same posture, the moving distance of center of gravity was about 56 mm. This motion is not easy for the elderly or injured people. In the future plan, we will propose the mechanism for moving center of gravity.

Conclusion

In this study, a step climbing method for a five-wheeled wheelchair was proposed, and an add-on drive mechanism to realize this method was developed. The proposed mechanism could not only perform the step climbing method but also the previous functions of the wheelchair. Because the five-wheeled wheelchair has five points of contact with the ground, its increased stability allows the front casters or the large wheels to hover above the ground at the height of the step, as required by the proposed method. Moreover, a step climbing process of the drive wheel using cooperative control of the linear actuator and the drive wheel was proposed. The suggested step climbing method was compared with a method that uses only the traction force of the drive wheel, and its advantage in climbing over a high step was confirmed. To realize the proposed method, an add-on drive mechanism was developed, and the design conditions required for this mechanism were analyzed. Finally, a prototype was constructed and used to experimentally verify that a wheelchair user could climb over a high step safely using the proposed method and mechanism.

In future studies, a descending system for the wheelchair with the proposed mechanism will be recommended, and a control system for automating the step climbing mechanism recursively will be constructed. Also, we will propose the mechanism for moving center of gravity and the method to climb stairs.

Consent

Written informed consent was obtained from the patient for the publication of this report and any accompanying images.

Additional file

Additional file 1: Movie related the experimental results shown in Figure 16. The five-wheeled wheelchair can climb over a step by the proposed method. Three tracks, the front caster, the large wheel, and the drive wheel, are measured by three markers.

Competing interests
The authors declare that they have no competing interest.

Authors' contributions
YM derived the basic concept of the overall system, technically construction the system and drafting the manuscript. MW suggested the construction of the article and helped with the editing of the manuscript. Both authors read and approved the final manuscript.

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Received: 22 October 2014 Accepted: 16 January 2015
Published online: 24 February 2015

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