Passive Add-On Mechanism for Electric Wheelchairs to Support Step Climbing Using Rider Motion

Kento Koizumi, Modar Hassan, *Member, IEEE*, Masakazu Hirokawa, *Member, IEEE*, and Kenji Suzuki

***Abstract*—In this letter, we propose a method for electric wheelchairs to climb steps using a passive add-on mechanism. The mechanism utilizes the rider's postural shift motion and canes to enable independent step climbing without the need for caregiver support. In this mechanism, auxiliary wheels are affixed behind the rear wheels of the wheelchair via a hinge joint. Step climbing is accomplished by 1) elevating the front wheels using the canes, followed by 2) raising the rear wheels onto the step using the spring force stored in the add-on mechanism and the rider's postural shift movement. To optimize the link lengths and springs of the add-on mechanism, we developed a quasi-static step-climbing model. Subsequently, we fabricated and tested a prototype of the add-on mechanism to validate its capability to ascend steps using the user's body power and postural shift. The experimental results confirm the system's ability to ascend a step approximately 23 cm in height within 15 seconds.**

***Index Terms*—Human-centered robotics, mechanism design, physical human-robot interaction.**

I. Introduction

WHEELCHAIRS serve as the primary means of mobility for individuals facing challenges in walking independently. The wheelchair market is expected to further expand in the coming years due to the aging population [1]. However, conventional wheelchairs often feature small caster diameters, posing difficulties in climbing steps. Despite global efforts to promote barrier-free accessibility, the rate of adoption of such measures in roads, urban parks, and buildings remains low. For instance, accessibility rate in Japan was less than 65% as of the end of fiscal years 2018 and 2019 [2]. While caregivers can aid wheelchair users in navigating steps and rough terrain, such assistance compromises the users' autonomy and imposes physical strain on the caregivers. Thus, developing wheelchairs that empower users to independently ascend steps remains a pressing need.

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Research on wheelchairs with enhanced functionalities has included models with specialized designs and mechanisms to climb steps [3], [4], [5], [6], [7]. Nevertheless, the increased weight and lack of foldability in such wheelchairs hinder their transportation, limiting their practicality for outdoor mobility. Conversely, add-on mechanisms designed for attachment to commercially available wheelchairs offer potential advantages in mitigating added weight, maintaining foldability, facilitating transportation in vehicles, and enhancing the economic viability of the proposed solutions. Such add-on mechanisms may incorporate active components, actuators, or passive elements.

Prajapat et al. [8] and Dang et al. [9] have investigated the use of active components in mechanisms that can be attached to existing manual wheelchairs for stair climbing. Phannil et al. also introduced the concept of a track-based add-on mechanism [10], and Lehner Lifttechnik GmbH [11] has commercialized a similar system. These mechanisms facilitate climbing multiple steps with the assistance of a power source. However, they either still necessitate caregiver assistance [8], [9], or increase the overall weight of the wheelchair (up to 64 kg) [11], posing challenges in storage or maneuverability by the user when not in use.

As an alternative approach, Mori et al. proposed a step-climbing method employing the user's caster-lifting motion and an electric mechanism with a telescopic link to lift the front wheels [12]. Additionally, Munakata et al. suggested a method for ascending a step utilizing a wheelie with an active caster mechanism [13]. While these active add-on mechanisms reduce the total system weight, they require reliable control and a relatively longer time to climb a step.

Finally, as an example of a mechanism employing solely passive components, Kim et al. developed a station platform-fixed add-on mechanism to facilitate boarding a train [14]. Similarly, Hosaka et al. proposed a passive add-on mechanism that elevates a wheelchair when the rider applies a reciprocating motion on a lever [15], [16]. These systems enable users to board a train without the need for caregiver assistance or additional power sources, yet they are not suitable for outdoor mobility.

In this letter, we introduce a novel passive add-on mechanism designed to enable an electric wheelchair to ascend steps. The proposed method utilizes the rider's upper body motion to assist the wheelchair climb steps by storing and releasing energy in a compression gas spring. This passive mechanism, which is installed on an electric wheelchair that provides forward propulsion, aims to address traditional challenges associated with step climbing, such as increased weight and time, by leveraging the residual upper limb functions of the rider.

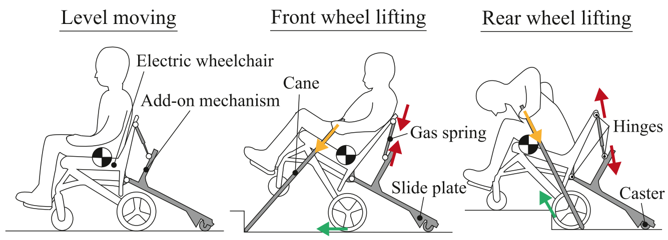

Fig. 1. Conceptual representation of the proposed step-climbing method.

Therefore, this letter primarily targets paraplegics with healthy upper limbs, particularly those who maintain an active lifestyle and can independently bend over, as the operation of the proposed step-climbing mechanism necessitates a certain level of upper-body muscle strength and postural adjustment. The main contributions of this letter include: the conceptualization of step climbing leveraging residual upper body function, the modeling and mechanical analysis of the interaction between the rider and wheelchair, and the considerations for the design of the passive add-on mechanism. Furthermore, the feasibility of this approach was assessed through experiments involving a prototype of the add-on mechanism affixed to a commercial wheelchair.

II. Methodology

A. Mechanism Overview

Fig. 1 illustrates a conceptual representation of the proposed step-climbing method. The passive add-on mechanism is configured as a slider-crank mechanism, comprising three rotary joints and one linear gas spring as a sliding joint. A linked pair of the mechanism is affixed to the left and right sides of the rear section of the wheelchair, as depicted in Fig. 6. The articulation of the add-on mechanism compresses the gas spring in response to the backward tilt of the wheelchair body, thereby lifting the front wheels. Subsequently, the forward tilt of the wheelchair, which raises the rear wheels, is facilitated by the extension of the gas spring. This fundamental operation of the mechanism enables the storage and release of energy using the gas spring.

B. Procedure for the Proposed Step-Climbing Method

The procedure for ascending a step is as follows. Initially, while approaching a step, the user lifts the front wheels by positioning the tip of both canes at the boundary between the step and the ground and pushing them with his/her hands. Once the front wheels are raised to the height of the step, the rider advances forward with the electric wheelchair while maintaining the elevation of the front wheels. During this phase, the wheelchair advances forward with support from the rear wheels and casters. Upon placing the front wheels on the step, the lifting of the front wheels is completed, and the energy generated by tilting the wheelchair is stored in the gas spring.

Subsequently, as the rear wheels make contact with the face of the step, the rider adopts a forward-bent posture to initiate the lifting of the rear wheels. This change in posture shifts the rider's center of mass forward, reducing the total torque required to lift the rear wheels. The rider then positions the canes behind the

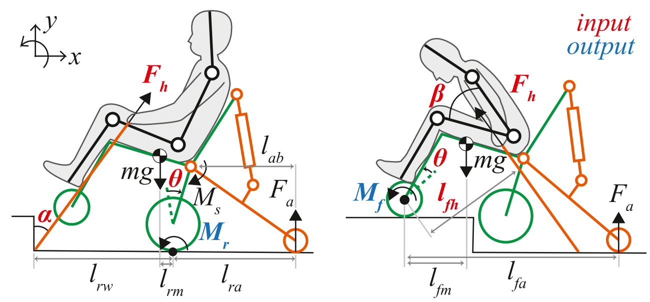

Fig. 2. Models of the rider and wheelchair with the passive add-on mechanism (left: Front wheel lifting, right: Rear wheel lifting).

rear wheels and applies upward pressure while simultaneously operating the electric wheels forward. The combined force of the canes pushing upward and the force generated by the gas spring achieves the lifting of the rear wheels. Following the successful lifting of the rear wheels, the auxiliary wheels ascend the step, thereby completing the step-climbing procedure.

C. Modeling of the Proposed Step-Climbing Method

We developed a model of the rider and wheelchair during front-wheel and rear-wheel lift to determine the conditions necessary for the passive add-on mechanism to ascend a step. For safety considerations, we assume that the rider and wheelchair move slowly during the step-climbing process and thus constructed a quasi-static model. Given the connection between the rider and the wheelchair via a belt, we presume that the force exerted through the canes is directly transmitted to the wheelchair. The rider is represented using four links, as depicted in Fig. 2, with gravity acting at the center of each link. Additionally, we assume negligible friction force between the auxiliary wheels and the ground. The conditions established through this model will inform the optimization of the link lengths and gas spring in subsequent sections. Based on these findings, we will proceed to design and develop a prototype to assess the feasibility of this method.

1) Quasi-Static Model for Front Wheel Lifting: During front wheel lifting, the front wheels are raised while the rear wheels remain locked. Consequently, the wheelchair rotates around the contact point between the rear wheels and the ground.

The model illustrated in Fig. 2 depicts the front wheel lifted after the rear wheels have rotated $-\theta$ around the rear axle from the level moving phase. Since the wheelchair maintains a static state, the equilibrium of moments around the center of the rotating pair can be applied to the wheelchair frame. Assuming that the horizontal distance between the rotating pair and the auxiliary wheel is represented by l_{ab} and the moment of the gas spring around the rotating pair is denoted as M_s, which is dependent on θ, the normal force F_a acting on the auxiliary wheel can be expressed by the following equation:

$$F_a = \frac{M_s(\theta)}{l_{ab}(\theta)} \tag{1}$$

Defining the cane pushing force exerted by the rider as F_h, the gravity force acting on the wheelchair and rider as mg, the angle between the cane and the vertical plane as α, and the horizontal distances between the rear wheel, auxiliary wheel, center of gravity, and step as l_{ra}, l_{rm}, and l_{rw}, respectively, which depend on θ, the moment M_r around the center of the rear wheel contact point can be expressed as a function of F_h, α and θ by the following equations: where M_{ra} represents the moment due to F_a, and M_{rh} represents the moment due to mg and F_h.

$$M_{ra} = F_a(\theta)l_{ra}(\theta) \tag{2}$$

$$M_{rh} = mgl_{rm}(\theta) - F_h l_{rw}(\theta)\cos\alpha \tag{3}$$

$$M_r = M_{ra}(\theta) + M_{rh}(F_h, \theta, \alpha) \tag{4}$$

When the rider applies force to the canes, frictional force acts on the rear wheel. If this frictional force exceeds the maximum static friction force, the rear wheels will slip, preventing the lifting of the front wheel. The condition for F_h to prevent slipping of the rear wheels is expressed by the following inequality, utilizing the static friction coefficient μ and the moment equilibrium formula $M_r = 0$. The maximum value of F_h at this point is defined as $F_{f\,\max}$:

$$F_h < \frac{mgl_{ra}(\theta)}{l_{rw}(\theta)\cos\alpha + l_{ra}(\theta)(\cos\alpha + \frac{\sin\alpha}{\mu})} \overset{\text{def}}{=} F_{f\,\max} \tag{5}$$

If $M_r < 0$ is satisfied when inequality (5) holds true, the wheelchair can rotate backward around the rear wheel contact point without slipping. Therefore, the following inequalities and inequality (5) hold simultaneously. The minimum value of F_h at this point is defined as $F_{f\,\min}$:

$$M_{ra}(\theta) + M_{rh}(F_h, \theta, \alpha) < 0 \tag{6}$$

$$F_h > \frac{F_a(\theta)l_{ra}(\theta) + mgl_{rm}(\theta)}{l_{rw}(\theta)\cos\alpha} \overset{\text{def}}{=} F_{f\,\min} \tag{7}$$

2) Quasi-Static Model for Rear Wheel Lifting: During rear wheel lifting, the rider pushes up with the canes, and the energy stored in the passive add-on mechanism, along with the driving force of the electric wheelchair, causes the wheelchair to rotate forward around the front wheels while moving forward. This motion is divided into the rotation around the front wheels of the wheelchair and the forward motion. As the rear wheels are lifted, the rider assumes a forward-bent posture, shifting the center of gravity toward the front of the wheelchair and reducing the necessary rotational moment. This posture shift is also considered as a new input to construct the model of the rider and the wheelchair.

The model depicted in Fig. 2 illustrates the rear wheels being lifted by rotating θ around the front wheel axis from the front wheels being placed on the step. The wheelchair rotates until the rear wheels reach the height of the step. To incorporate the posture shift of the rider into the model, the rider is assumed to adjust the center of gravity by changing the rotation angle β of the hip joint. The horizontal distance l_{fm} from the front wheels to the center of gravity is determined by the function f_m with θ and β as inputs, as follows:

$$l_{fm} = f_m(\theta, \beta) \tag{8}$$

The driving force of an electric wheelchair contributes to rear wheel lifting only when the rear wheels are in contact with a step, but the moment varies significantly depending on the size and position of the rear wheels and the step. Assuming the worst-case scenario, the moment due to the driving force is ignored. In this case, assuming that the horizontal distance between the front wheels and the auxiliary wheels is l_{fa} and the distance between the front wheels and the cane is l_{fh}, the moment M_f at the center of the front wheels' rotation axis can be expressed as a function of F_h, l_{fh}, θ, and β by the following formulas: M_{fa} represents the moment due to F_a, while M_{fh} represents the moment due to mg and F_h. F_a is calculated using (1), and other variables are assumed to have the same value as that of Section II-C1:

$$M_{fa} = F_a(\theta)l_{fa}(\theta) \tag{9}$$

$$M_{fh} = -mgl_{fm}(\theta, \beta) + F_h l_{fh} \tag{10}$$

$$M_f = M_{fa}(\theta) + M_{fh}(F_h, l_{fh}, \theta, \beta) \tag{11}$$

To achieve rear wheel lifting, the wheelchair must be capable of rotating forward about the center of the front wheel rotation axis, meaning the equation $M_f > 0$ must hold. Therefore, if the wheelchair is capable of rear wheel lifting, the following inequality holds. The minimum value of F_h at this point is defined as F_{rmin}:

$$M_{fa}(\theta) + M_{fh}(F_h, l_{fh}, \theta, \beta) > 0 \tag{12}$$

$$F_h > \frac{-F_a(\theta)l_{fa}(\theta) + mgl_{fm}(\theta, \beta)}{l_{fh}} \overset{\text{def}}{=} F_{r\,\min} \tag{13}$$

By designing the passive add-on mechanism so that inequalities (5), (6), and (12) are satisfied, respectively, the wheelchair can climb the step.

D. Design Requirements for the Passive Add-On Mechanism

To design a passive add-on mechanism that facilitates both front wheel lifting and rear wheel lifting, it is essential to select appropriate link lengths and gas springs. As evident from inequalities (7) and (13), the minimum value of F_h fluctuates between phases, depending on F_a, which is proportional to the reaction force of the gas spring, during the lifting of the front and rear wheels. Therefore, to account for both phases, the gas spring should be chosen to ensure similarity in the force required to push the cane out. Once the reaction force of the gas spring and the frame lengths are determined from (1), F_a is ascertained. By predefining the other parameters, inequalities (7) and (13) can theoretically be utilized to derive the minimum value of F_h when the moment around the wheel is set to zero. To this end, optimal parameters are determined by adjusting the link lengths and springs in accordance with the following requirements:

- Minimize F_h required for front and rear wheel lifting
- Ensure satisfaction of inequalities (5) and (6) for front wheel lifting and inequality (12) for rear wheel lifting
- Maintain gas spring stroke within specified limits
- Prevent collisions between the mechanism and wheelchair frame

Subsequently, the target step height is set to 23 cm, following the Japanese building standard law [17].

TABLE I
SPECIFICATIONS OF THE ELECTRIC WHEELCHAIR WITH THE DEVELOPED PASSIVE ADD-ON MECHANISM

Dimensions	Width	560	mm
	Length	1410	mm
	Height	930	mm
	Front wheel diameter	175	mm
	Rear wheel diameter	270	mm
	Front and Rear wheelbase	510	mm
Weight	Overall	27.0	kg
	The developed mechanism	5.3	kg

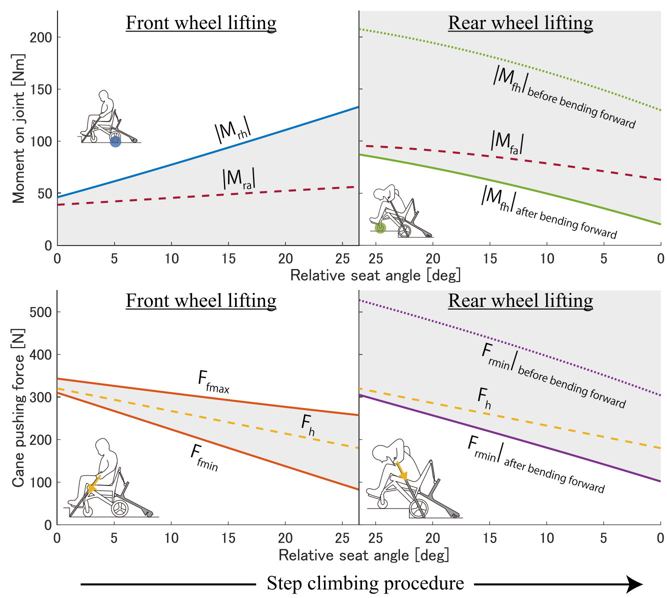

Fig. 3. Relationship between seat angle and the moment around the axis of rotation/cane pushing force. M_{rh} represents the moment around the rear wheel contact point due to gravity force and F_h, while M_{ra} represents the generated moment by gas springs in front wheel lifting. M_{fh} represents the moment around the front wheels' rotation axis due to gravity force and F_h, while M_{fa} represents the generated moment by gas springs in the rear wheel lifting. $F_{f\,\max}$ represents the maximum force until the rear wheel slips in front rear lifting, while $F_{f\,\min}$ represents the minimum force to lift the front wheel. $F_{r\,\min}$ represents the minimum force to lift the rear wheel, while F_h represents the cane pushing force exerted by the rider.

III. PROTOTYPE DESIGN

A. Optimization of the Passive Add-On Mechanism

Based on the models described in Sections II-C1 and II-C2 and the design requirements outlined in Section II-D, we will optimize the cane pushing force (F_h) and select appropriate gas springs and frame link lengths for the passive add-on mechanism. Simulation was employed to calculate F_h and choose gas springs and frame lengths that minimize the peak force of F_h. For this letter, a commercial electric wheelchair was utilized to develop the prototype. The overall specifications of the wheelchair are detailed in Table I. The target user was characterized as a young adult (22-year-old male, 172 cm in height, and 56.8 kg in weight) with no history of neurological or musculoskeletal disorders, serving as the initial target to verify the feasibility of the proposed method.

The state transition diagram of the moment and force obtained through optimization is depicted in Fig. 3. The horizontal axis

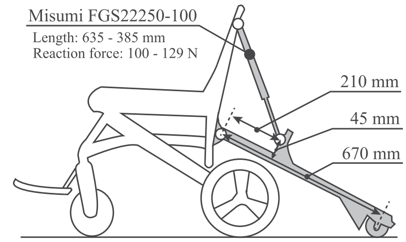

Fig. 4. Optimized frame length and selected spring characteristics.

illustrates the seat angle of the wheelchair from the initial state, while the vertical axis represents the moment around the rotation axis and the cane pushing force. Progression from left to right in the diagram corresponds to the step-climbing procedure. The top figure in Fig. 3 displays the moment around the rear wheel contact point (left) and the moment around the front wheel rotation axis (right). The solid lines denote M_{rh} obtained from (3) and M_{fh} obtained from (10), respectively. In the rear-wheel lift, the dotted line represents M_{fh} before the rider is bent forward, subsequently reduced to the solid line by the rider's posture change. The dashed lines signify M_{ra} obtained from (2) and M_{fa} obtained from (9), respectively. The gray area indicates the range of M_{ra} and M_{fa} when inequalities (5), (6), and (12) are satisfied. As evident from Fig. 3, the dashed lines fall within the gray area, signifying compliance with the design specifications. All of these moments are calculated as positive values to facilitate visual comparison.

The bottom figure in Fig. 3 illustrates F_h exerted by the rider. The gray area depicts the range of F_h when inequalities (5), (7), and (13) are satisfied. The dashed line represents the scenario where the rider applies a linear force ranging from 320 N to 180 N, and the moments in the above figure correspond to this force. F_h needed for the rider to climb a step is highest at the initial stage of each wheel lifting and decreases as the seat is tilted. The minimum value of F_h required by the rider is 311 N. The characteristics of the optimized link lengths and the selected spring (Misumi FGS22250-100) are depicted in Fig. 4.

B. Range of Application of the Rider to the Designed Mechanism

The average shoulder extension force of paraplegics with healthy upper limbs has been reported as 397 ± 125 N in their 20 s, 444 ± 98 N in their 30 s, and 370 ± 98 N in their 40s [18], which falls within an acceptable range. Furthermore, according to the study by Wiyanad et al. [19], the seated push-up test result of individuals with spinal cord injuries was 483 ± 94 N. This suggests that end users can exert sufficient force even in a posture similar to that during rear wheel lifting.

The passive add-on mechanism, designed based on the optimal values derived in Section III-A, is expected to be applicable to individuals within a limited range of body height, body weight, and F_h. We assessed the F_h required in response to changes in body weight and height using inequalities (7) and (13). Body weight is determined considering Matsui's body part mass ratio [20], while body height is based on the AIST/HQL

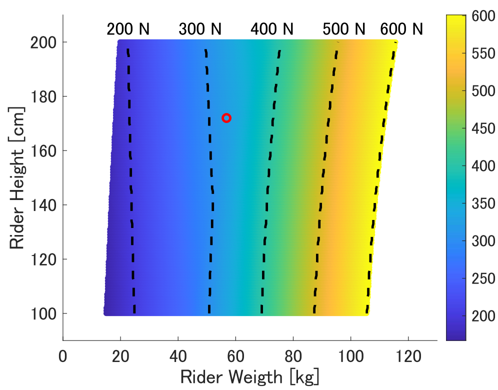

Fig. 5. Rider Range of application for the designed mechanism. The colors in the graph indicate the distribution of the required F_h [N]. The black dotted line represents the curve for each 100 N from 200 to 600 N. The red circle denotes the height and weight of the participant in this experiment.

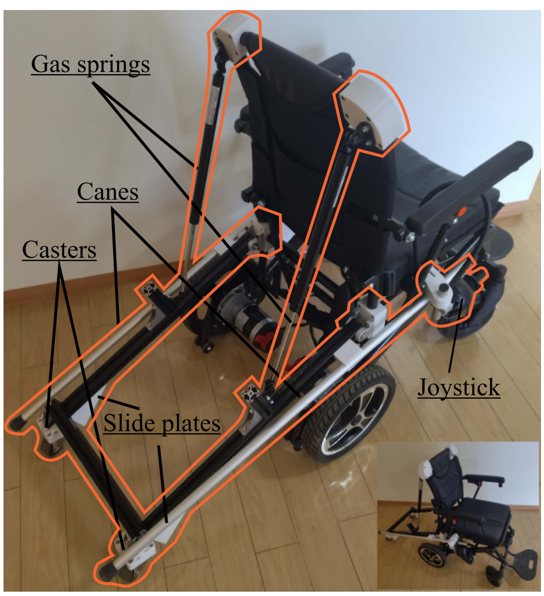

Fig. 6. Electric wheelchair featuring the developed passive add-on mechanism.

Human Body Dimension and Shape Database 2003 [21]. In this calculation, the rider's height is confined to 100 cm to 200 cm.

The calculated results are presented in Fig. 5. The horizontal axis represents the rider's body weight, and the vertical axis represents the body height. The colors in the graph indicate the distribution of the required F_h. It can be observed that F_h depends more on body weight than on height. Specifically, the greater the rider's weight, the higher the F_h required.

C. Developed Prototype

A prototype of the proposed method was developed using an electric wheelchair with the passive add-on mechanism, as depicted in Fig. 6. The passive add-on mechanism comprises 3D-printed fixations to the wheelchair, aluminum frames, gas springs, casters, hinge pins, bearings, slide plates for lifting the auxiliary wheels, and canes. The total length of the cane was set to 1000 mm, with the length of the grasping part at 160 mm. The position of the grasping part can be adjusted according to the user's requirements. In the subsequent experiments, the grasping part's position was fixed at 900 mm from the tip of the cane. The canes are stored on the frame of the passive add-on mechanism when not in use for climbing steps, as illustrated in Fig. 6. The overall dimensions and weight are detailed in Table I.

IV. Performance Evaluation

Experiments were conducted to evaluate the proposed method of step climbing. Initially, we assessed the required force (F_h) exerted by a user through the canes to achieve front and rear wheel lifting, as well as the feasibility of climbing a step without the passive add-on mechanism. Subsequently, a step-climbing test was conducted with the proposed method utilizing the canes and the passive add-on mechanism.

A. Evaluation of the Force Required for Wheel Lifting

Tests were conducted to assess front and rear wheel lifting attempts to ascend a single step with a height of 23 cm using the canes and the electric wheelchair, both with and without the passive add-on mechanism. A force gauge (IMADA ZTA-2500 N) was affixed to the cane, and the participant was instructed to exert full force equally with both arms while seated in the wheelchair. Concurrently, the seat angle was measured to explore the correlation between the seat angle and F_h. The participant in the experiment was the same as in Section III-A, and the force was sampled at 50 Hz in five measurements for each condition. To evaluate the auxiliary effect of the add-on mechanism, the overall energy consumption was calculated using the following equation and compared with and without it. The overall energy consumption is defined as the integral value I of F_h across all angles:

$$I = \int F_h(\theta) d\theta, \quad (0 \leq \theta \leq 26)\,\text{deg} \tag{14}$$

The results are depicted in Fig. 7. The horizontal axis illustrates the angular change of the wheelchair seat from the initial position, while the vertical axis represents F_h on one side. This graph displays the mean and standard deviation values of the five measurements. Wheel lifting was successfully achieved in all trials, both with and without the add-on mechanism. Based on the results illustrated in Fig. 7, the total workload I was calculated as $4752\,\text{N} \cdot \text{deg}$ with the add-on mechanism and $4417\,\text{N} \cdot \text{deg}$ without it. The peak values of the mean F_h were 83 N for front wheel lifting and 204 N for rear wheel lifting without the add-on mechanism. Conversely, with the mechanism, these values were 141 N and 143 N, respectively.

B. Evaluation of the Feasibility of Step Climbing

Experiments were conducted using the developed prototype (Fig. 6) to assess the feasibility of step climbing with the proposed method. In the experimental procedure, the participant from Section III-A ascended several single steps (with heights of 9 cm, 16 cm, and 22 cm, respectively) and two steps (with a riser of 9 cm and a tread of 70 cm) outdoors using the prototype. Additionally, a single 23 cm step was climbed. The time required

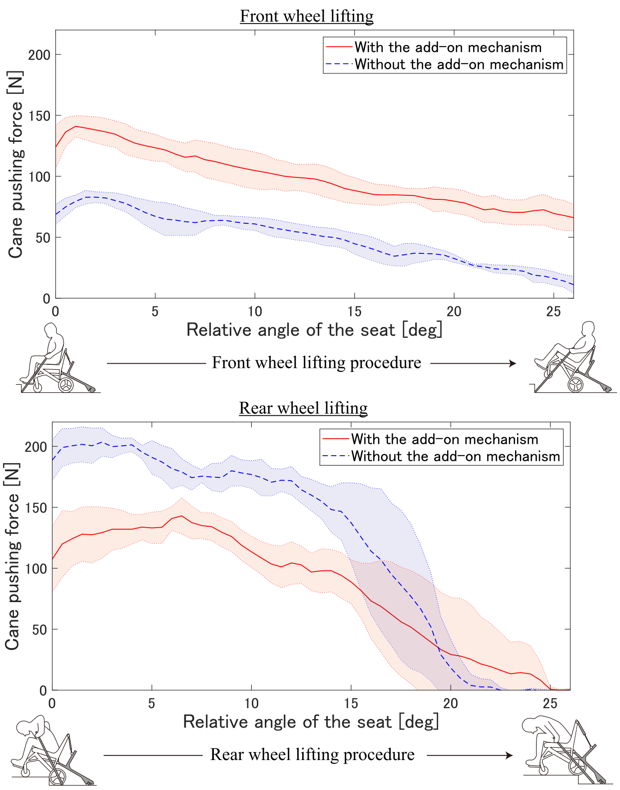

Fig. 7. Mean and standard deviation of F_h on one side in relation to the angular change of the seat during front wheel lifting (top) and rear wheel lifting (bottom).

to climb the $23\,\mathrm{cm}$ step was measured five times, and the mean time required along with its standard deviation are reported.

Fig. 8 illustrates the sequence of climbing the $23\,\mathrm{cm}$ step. The results confirmed the successful ascent of all steps following the procedure outlined in Fig. 8. Furthermore, it was observed that by moving the wheelchair backward, the rider could descend the step without utilizing the canes. During descent, a slight shock was experienced upon the front wheels landing on the bottom of the step. The time taken to ascend a $23\,\mathrm{cm}$ step averaged $14.6 \pm 2.07\,\mathrm{s}$, while descending took $5.2 \pm 0.84\,\mathrm{s}$.

V. Discussion

In Fig. 7(top), it is observed that the force applied using the canes, F_h, was greater with the passive add-on mechanism to lift the front wheels. This is attributed to the additional force needed to compress the gas spring. Conversely, during rear wheel lifting, F_h at the beginning of the lifting process was greater with than without the add-on mechanism. With the add-on mechanism, the energy stored by the gas spring during front wheel lifting was released, thereby reducing F_h for rear wheel lifting. Rear wheel lifting using the cane alone would necessitate a considerable amount of force and may not be achievable. With the add-on mechanism, it was confirmed that the required force can be reduced to a range achievable by prospective wheelchair users, which is less than half of the mean shoulder extension force of males with paraplegia in their 20 s to 40s [18], and the mean push-up force of $483\,\mathrm{N}$ for persons with spinal cord injury [19]. This supports the feasibility of the proposed mechanism when introduced to wheelchair users. This result suggests that the reduction in peak force due to the add-on mechanism does not significantly increase the overall energy consumption for climbing a step, besides potential mechanical losses in the mechanism itself.

As shown in Fig. 7(bottom), the standard deviation of F_h increased after the seat angle reached 15 degrees in rear wheel lifting. This variability could be attributed to the timing variability at which the rider raises the body from the forward-bent posture in each trial, and the required F_h changes after the middle stage of rear wheel lifting. It was also noted that F_h without the add-on mechanism dropped sharply after about 15 degrees. Without the add-on mechanism, the participant's posture was more rigid due to the full effort to push the cane, resulting in less posture changes and consequently lower required F_h compared to that with the add-on mechanism. Fig. 3 illustrates that F_h required for rear wheel lifting varies significantly depending on the posture shift.

With the add-on mechanism, the maximum force for front and rear wheel lifting is close to $150\,\mathrm{N}$. This confirms the successful functioning of the add-on mechanism as described in Section II-D. This also establishes a balance in both phases of step climbing, which is expected to enhance the operability of the system for end users. Nonetheless, reducing the value of F_h will enable a broader range of wheelchair users to utilize this system.

A step-climbing experiment confirmed that the participants could climb a step of $23\,\mathrm{cm}$ using the proposed method. The $23\,\mathrm{cm}$ step was ascended in $14.6 \pm 2.07\,\mathrm{s}$, which is shorter than the time required by the passive mechanism methods presented in the related studies (Table II). This efficiency is believed to stem from the rider's upper body motion, which can be effectively utilized to climb a step by the passive mechanism that accumulates and releases energy. The rider's posture shift reduces the rotational moment required to ascend a step. However, end users employing the system may encounter limitations in the force that can be generated by their upper limbs to initiate and complete the step-climbing process, and the ability to generate such force while in the forward bent posture as shown in Fig. 8, No.5, could be restricted depending on the individual's upper body capabilities. The experiment also validated the capacity to ascend and descend stairs with large treads. The auxiliary wheels extend behind the rear wheels, particularly crucial in rear wheel lifting and step descent to ensure stability and prevent backward falls. However, when descending a step, the front wheels experience a slight shock upon landing on the ground, which may be non-negligible for wheelchair users with lower limb disabilities. Therefore, measures to mitigate this shock, such as introducing a shock absorption element to the front wheels, need consideration. Additionally, it is essential to visually assess the height of the step before lifting the wheelchair and maintain appropriate force until the front wheels are on the step (Fig. 8, No.3). Operating the joystick while pushing the cane out during wheel lifting is challenging due to the significant physical effort required. Hence, improving the interface of the

Fig. 8. Sequence of 23 cm step climbing: 1. Placing the canes in front of the step. 2. Lifting the front wheels by pushing the canes. 3. Driving forward the wheelchair. 4. Placing the canes behind the wheelchair. 5–7. Lifting the rear wheels by pushing the canes. 8. Driving forward the wheelchair to engage the passive add-on mechanism on the step.

TABLE II
COMPARISON OF STEP-CLIMBING METHODS WITH AN ADD-ON MECHANISM

Research	Wheelchair	Add-on mechanism	Max height [cm]	Time [sec]	Weight [kg]
Prajapat [8]	Manual	Active	17	-	20
Dang [9]	Manual	Active	20	4 (/1step)	40
Phannil [10]	Electric	Active	20	4 (simulation)	~200
Mori [12]	Manual	Active	15	45	5.8
Munakata [13]	Manual	Active	10	120	-
Kim [14]	Manual & Electric	Passive	10	27	16
Hosaka [15] [16]	Manual	Passive	20	about 35	18.45
Proposed method	Electric	Passive	23	15	5.3

cane, for instance, by restricting its articulation relative to the wheelchair frame, is necessary to enhance ease of operation.

A comparison of different methods for step climbing with an add-on type mechanism attached to a wheelchair is presented in Table II. The comparison reveals that the proposed method allows for climbing the highest step tread, 23 cm, in the shortest amount of time, 15 s, which is the shortest time among all passive mechanisms, and exhibits the least weight among the add-on mechanisms, at 5.3 kg. In contrast, the method proposed by Prajapat et al. [8] is adaptable to various types of steps, including outdoor stairs, but its add-on mechanism is too large and bulky for outdoor mobility. The method suggested by Dang et al. [9] enables ascending and descending stairs indoors but necessitates assistance from a caregiver. Although the method introduced by Phannil et al. [10] ensures safe stair ascent and descent using a crawler, the mechanism is heavy and challenging to transport. Mori et al.'s [12] method offers active assistance for step climbing but demands complex control and high reliability. Similarly, Munakata et al.'s [13] method provides active support for plantar locomotion and step climbing, yet it can only support 10 cm in 120 s. Kim et al.'s [14] approach can overcome both steps and gaps, enabling train boarding, but its add-on mechanism must be fixed to the station platform. Conversely, Hosaka et al.'s [15], [16] method requires time to lift the wheelchair, and its add-on mechanism is heavy. The primary drawback of the proposed method lies in the necessity for users to utilize canes to provide force for the step-climbing procedure, as well as the need to stow the canes when not in use. The authors contend that using canes is advantageous for maintaining users' upper body strength and leveraging their latent capabilities during locomotion. Nevertheless, the requirement to stow the canes on the wheelchair poses a hindrance. This issue will be addressed in future iterations by substituting the canes with attachments to the wheelchair and implementing a lever that can be manually operated by the user.

VI. CONCLUSION AND FUTURE WORKS

In this letter, we proposed a new passive add-on mechanism designed to assist wheelchairs in climbing outdoor steps. Furthermore, to validate the effectiveness and feasibility of the proposed method, we conducted experiments with a prototype wheelchair ridden by a young adult.

Because the upper body motion of the rider is necessary for step climbing, it is possible that wheelchair users with reduced ability levels and physical strength may face challenges in utilizing the mechanism. Therefore, in future research, we intend to conduct experiments with more diverse end users to assess the applicability of the proposed method across different user demographics.

The wheelchair equipped with the proposed mechanism can navigate outdoor environments without obstructing sidewalks or other surfaces, as its dimensions adhere to standard wheelchair specifications. Moving forward, we plan to investigate the implementation of a foldable structure for the add-on mechanism to enhance portability and convenience when not engaged in step climbing.

To facilitate step climbing without modifying existing electric wheelchairs, the extent of the rider's center of gravity shift is constrained by the wheelchair's design. Thus, developing wheelchairs that can fully utilize center-of-gravity shifts, possibly through features like reclining mechanisms and adjustable backrest seatbelt tensioning systems, could enable climbing higher steps and broaden the applicability of the mechanism to a wider user base. While the proposed method primarily employs a passive mechanism, exploring the integration of electric mechanisms, such as mechanisms to reduce F_h, could enhance its effectiveness for certain wheelchair users. Additionally, this method introduces a novel approach to step climbing using a cane, which could potentially be adapted for use in other mobility devices and robots traversing uneven terrain.

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