Stair-Climbing Mobility Device utilizing Mechanical Power Flow between Human and Machine

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Declaration of Authorship

I, Kai SASAKI, declare that this thesis titled, "Stair-Climbing Mobility Device utilizing Mechanical Power Flow between Human and Machine" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
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Abstract

In this research, we investigate, develop, and verify a methodology for step/stair-climbing with human and machine. Step/Stair-climbing mobility devices have been investigated in the field of mechatronics, but human capability has not always been utilized explicitly regardless of physical conditions. In this work, we propose a step/stair-climbing methodology which utilizes human capability using an appropriate mechanism towards human centered assistive devices.

We studied 3 step/stair-climbing mobility devices. First one is a stair-climbing mobility device with lever propelled rotary-legs using human upper body strength. Second one is an active rotary-legs mechanism for stair-climbing mobility device. Third one is a step-climbing methodology using a passive mechanical structure for standing mobility device. All of the mobility devices were studied based on a concept of mechanical power flow between human and machine. We also focused on an overall center of mass position as well as the power flow in the whole system including human, which realized the proposed step/stair-climbing with human and machine.

We verified the proposed mobility devices through a series of experiments. In the first study, we conducted experiments with healthy persons, a dummy, and people with spinal cord injury who use a manual wheelchair for their daily life. The results demonstrated that stair-climbing could be performed by user him/herself without any powered mechanisms. In the second study, we performed stair-climbing experiments with a dummy, and it demonstrated that stair-climbing could be done more efficiently in terms of energy consumption based on the concept of mechanical power flow. In the third study, we conducted step-climbing experiments with a dummy, and it showed a passive structure which can change an overall center of mass position and mechanical power flow was feasible. Throughout the experiments, we verified that position of the overall center of mass plays an important role for the proposed step/stair-climbing, which was realized by posture transition of a user. We also verified that designing mechanical power flow is another key point, which was realized by a mechanical structure which stores, divaricates, and releases energy appropriately.

The main contribution of this research is to introduce the methodology to perform step/stair-climbing using user's capabilities such as upper body strength to the field of existing step/stair-climbing mobility devices focusing on mechatronics. Also, this research shows guidelines as well as practical examples for designing future mobility devices for human centered assistive devices.

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Chapter 1

Introduction

1.1 Background

Mobility is defined in Cambridge Dictionary as the ability to move freely or be easily moved [1]. Historically, human beings have explored this world, have interacted with the environments and other humans through their mobility. In this day and age, we go to school, work, play, make a trip, visit friends, take a walk, and go wherever you want by our own mobility. Further, regardless of physical conditions, self-directed mobility is considered as a fundamental human right to fully participate in social life [2]. Self-directed mobility is defined as mobility that is controlled by an individual and may include walking, use of technology such as gait trainers, motorized wheelchairs, or other similar devices for supporting human locomotion [3, 4]. Self-directed mobility plays an important role for healthy development in childhood, and for self-esteem social life of each individual in adulthood. For instance, children's development including advancements in cognition, social, and language skills, and emotional development depends on perceptual-motor experiences obtained through the self-directed mobility [5, 6]. Also, we can involve in social life including establishing interpersonal relationships and engagement in community, social, and civic life [2, 3]. On the other hand, limited self-directed mobility often leads to decrease not only physical, but also psychological conditions, and opportunities to socialize, which often results in social isolation [7–10]. In addition, prevention and treatment of diseases in the locomotive functions and maintenance of motor functions are important for extended healthy life span and to decrease the demand for long-term care [11].

Around the world, there are a number of people who suffer from limited self-directed mobility due to lower limb impairments. For example, according to the Japanese Cabinet Office, it is estimated that there are approximately 630,000 people with lower limb impairments [12]. One of the major causes of the lower limb impairment is spinal cord injury (SCI). Spinal cord injury is a medically complex and life-disrupting condition, and refers to damage to the spinal cord arising from trauma such as accidents including car clash, falling, victim of conflict or gun violence [13]. There are over 280,000 people with spinal cord injury in the United States [14]. In addition, a global incident rate in 2007 is estimated at 23 traumatic spinal cord injury (TSCI) cases per million, which can be calculated as 179,312 cases per year. Specifically, the rate is 40.2 per million in Japan, and 54 per million in the United States [14, 15]. This corresponds to the fact that approximately 5,000 and 17,000 people newly suffer from the incidents every year both in Japan and the United States, respectively. Furthermore, TSCI in developed (high income) and developing countries primarily affects males aged 18-32 years old [15]. Therefore, a large number of young people have limited self-directed mobility in the prime of their life.

No effective standard of care has been established for people with spinal cord injury at this moment. Rehabilitation to relieve permanent damage can be considered as the standard of care for the people [16, 17]. Several therapeutic technologies have been proposed such as exoskeletons, functional electrical simulation to facilitate the rehabilitation training [18–20]. In addition, regeneration medical techniques using cell transplantation and stem cell are placed more expectations. However, it is almost impossible for people with spinal cord injury to regain their mobility completely. Under the current circumstances, people with spinal cord injury rehabilitate their injury to recover and retain the highest possible level of autonomy of them to maximize their social participation [21].

As we look forward their daily life, they often use wheelchairs to support their mobility. World Health Organization have reported that there were approximately 75 million people needed a wheelchair around the world [22]. Mobility can be supported by the wheelchairs. Also, manual wheelchairs are widely used for the people who have healthy upper limbs [23, 24], while powered wheelchairs are used by those who have limited upper body capabilities [25, 26]. Statistically, more manual wheelchairs are widely used compared to powered wheelchairs [27–29]. Locomotion capability of manual wheelchairs have been improved by utilizing unique mechanisms such as lever propulsion control in the past years, which leads to more efficient and suitable wheelchair propulsion design for physiological biomechanics of the upper extremity joints [30, 31].

Despite people with lower limb impairment use wheelchairs to regain their self-directed mobility, they encounter several critical problems. For instance, although the all advances of technologies, they are still forced to take a sitting posture on the wheelchairs, which would cause severe damages such as pressure sore. The arm's reach is also restricted compared to people who can stand, which makes them inconvenient in lots of places such as home, office, grocery. In addition, the eye level of wheelchair users is much lower than that of people who are standing, which degrades wheelchair user's self-esteem [32]. It would not be always comfortable for wheelchair users to live in such environments mostly designed for people who can stand and walk. Therefore, taking a standing posture is important for them; it has several benefits for not only daily activities, but also medical needs, bone metabolism and the circulatory system [33, 34]. To deal with the serious issue, mobility devices for assisting posture transition between sitting and standing have been proposed thus far [35–37]. Also, child-sized passive exoskeleton for supporting the posture transition and toilet usage [38] has been proposed based on the research result [37]. Further, some of the standing mobility devices have been commercialized in different countries [39–41]. Therefore, wheelchair users are in the process of regaining a choice of standing.

Another serious problem for wheelchair users is that they encounter critical obstacles such as steps and stairs when using wheelchairs [42, 43]. To deal with steps, wheelchair users are supposed to acquire certain wheelchair skills such as wheelie [44, 45]. However, not every wheelchair users can perform the wheelie due to inadequate training, and limited upper body capabilities. One report says that almost all of elderly wheelchair users cannot overcome a single step whose height is over 20 mm [46]. Also, wheelchair users cannot overcome stairs only by the wheelie motion. Regardless of their upper body capabilities, they often require at least one helper to overcome steps and stairs. This circumstances often cause wheelchair users to stay indoors, which leads to decrease their physical and mental health. Regarding standing mobility devices, it is quite dangerous for users to overcome even a small single step with the standing posture, since the center of mass (COM) of whole system tends to be higher than that with the sitting posture. Although barrier-free public spaces where slopes, elevators, etc. are implemented have been promoted so far, it is almost impossible to implement them in all public spaces. Also, in the case of evacuation, elevators cannot be used during disasters such as earthquakes; thus overcoming steps and stairs inevitably be a critical issue to be dealt with for wheelchair users.

1.2 Related Works

To deal with the critical issue of step/stair-climbing, the development and assessment of step/stair-climbing mobility devices have been conducted thus far. Design of step/stair-climbing mechanisms directly affect the step/stair-climbing capability including control complexity, cost, energy consumption, step/stair adaptability, etc. In general, step-climbing mechanisms are mechanically simple and easy to implement to a regular wheelchair, which extends step-climbing functionalities while maintaining planar locomotion capability. On the other hand, stair-climbing mechanisms are designed to climb up and down different stair height and tread safely, which leads to the mechanisms be more complicated.

First, to the author's best knowledge, step-climbing mechanisms are classified into three categories: unique caster, add-on, and deformation-based mechanism.

- Unique caster mechanism: One of the primary reasons that wheelchairs cannot overcome a step is that they are often equipped with small radius of casters for compactness. It requires certain amount of driving force which some wheelchair users such as elderly cannot exert by pushing a hand rim using their upper body. Therefore, some unique casters to reduce the driving force have been proposed so far [47, 48]. Although the required driving force can be reduced, its step-climbing capabilities is still limited since most of the proposed mechanisms are based on a small radius of casters.

- Add-on mechanism: An add-on mechanism is defined in this study as a mechanism that can be easily attached/detached to a regular wheelchair to improve its step-climbing performance. This mechanism usually consists of motorized wheels, and/or additional powered mechanisms such as slider, and linkage mechanisms [49, 50]. The mechanisms usually assist to perform wheelie motion automatically to overcome a single step. Thus, the mechanism is usually attached at the rear of wheelchairs.

- Deformation-based mechanism: A deformation-based mechanism is defined in this study as a wheeled mechanism which has passive structures to overcome steps and stairs. In general, this mechanism is designed for rovers to overcome rough terrain including a single step [51–53]. The mechanism deforms passively to overcome target steps and stairs when contacting with them. The mechanisms usually make use of reaction forces so that they can overcome the steps and stairs by changing their configurations passively.

Second, to the author's best knowledge, stair-climbing mechanisms are classified into four categories: crawler-based, leg-based, multi-wheels-based, and hybrid mechanism.

- Crawler-based mechanism: A crawler-based mechanism utilizes endless chain belts for travelling, which is mechanically simple and easy to control. It also has large contact areas with stair surface, which can ensure high stability during stair-climbing. However, its energy efficiency and speed for planar locomotion are relatively low compared to other stair-climbing mechanisms [54–57].

- Leg-based mechanism: A leg-based mechanism is designed based on locomotion technique of animals including human. It has flexible three-dimensional locomotion capability, and high adaptability to various stair dimensions. However, its mechanism and control are usually complicated, and its energy efficiency and planar locomotion speed are relatively low [58–60].

- Multi-wheels-based mechanism: A multi-wheels-based mechanism is an assembly part by combination of multi wheels, where each wheel is distributed around a same rotational center. The mechanism utilizes its rotational motion of the assembly part to climb up and down stairs [61–64]. The mechanism is simple and easy to control, and has high energy efficiency. However, the climbing process would be uncomfortable for users because of its waving motion by rotating the assembly part. In addition, it usually needs at least one helper to secure user's safety during stair-climbing.

- Hybrid mechanism: A hybrid mechanism is defined in this study as a mechanism which combines aforementioned mechanisms to secure each advantage while decreasing each disadvantage [65–68]. One of the examples for hybrid mechanism is the wheel-leg mechanism [65]. The mechanism uses wheels for planar locomotion, and uses a leg mechanism for stair-climbing. Although the mechanism can be considered as a great innovation, it is still larger, and tends to become more complicated mechanism.

As overall trend, almost all of them use powered mechanisms regardless of their step/stair-climbing mechanism, because wheelchair users want to overcome steps and stairs alone to perform their independent social activities. However, most of the users use manual wheelchairs in their daily life. Although powered step/stair-climbing mobility devices play significant role for people with lower limb impairment [69, 70], shifting from manual wheelchairs to powered mobility devices for only overcoming steps and stairs cannot be always desirable from the viewpoint of maintenance of physical fitness as well as size, weight, energy efficiency, and cost [71, 72].

Furthermore, almost all of the related researches considered a user as a weight that can control the step/stair-climbing mobility device via an interface such as a joystick even in the case that the user has healthy upper body strength. Such users can propel manual wheelchairs using their upper body strength to move around in public spaces. Therefore, I consider that the area of step/stair-climbing mobility devices leaves an important room for considering a possibility to overcome steps and stairs by user him/herself with appropriate mechanisms.

1.3 Research Question

Research of step/stair-climbing mobility devices from the view point of mechatronics has been performed so far, which would correspond to the fact that almost all of related researches focused on only design of mobility device itself. It does not include human explicitly. Towards life with self-esteem and independence for human, I discuss the following research question throughout this study:

- What is the step and stair-climbing with human and machine?

Exploration for answering this question would provide not only design requirements for step/stair-climbing with human, but also some insights to design future human centered mobility devices that improve user's independence, which would be integrated into our everyday life.

To explore the research question, I hypothesized about the step/stair-climbing with human and machine as follows:

- I predict that a user ' s posture on a mobility device affects its locomotion capability, e.g., for both planar locomotion and step/stair-climbing.
- I predict that some wheelchair users can climb steps and stairs by themselves using a proper mechanism with an appropriate posture for step/stair-climbing.
- I predict that designing physical interactions among all elements including human would be one of key points.

Based on the hypotheses, I conducted the research.

1.4 Objectives

Figure 1.1 shows an overview of this research. The research objective is to establish a step/stair-climbing methodology for wheelchair users that performs step/stair-climbing using user's capabilities such as upper body strength, with appropriate mechanisms. This research focuses on exploiting mechanical power flow between human and machine for human centered design. Based on the mechanical power flow, appropriate physical interactions between human and machine are designed. This research mainly focuses on extending functionalities of regular wheelchairs. However, since standing mobility devices are placed more expectations for future locomotion supporting devices, the research also focuses on extending functionalities of standing mobility devices.

In this research, following 3 case studies have been performed in sequence:

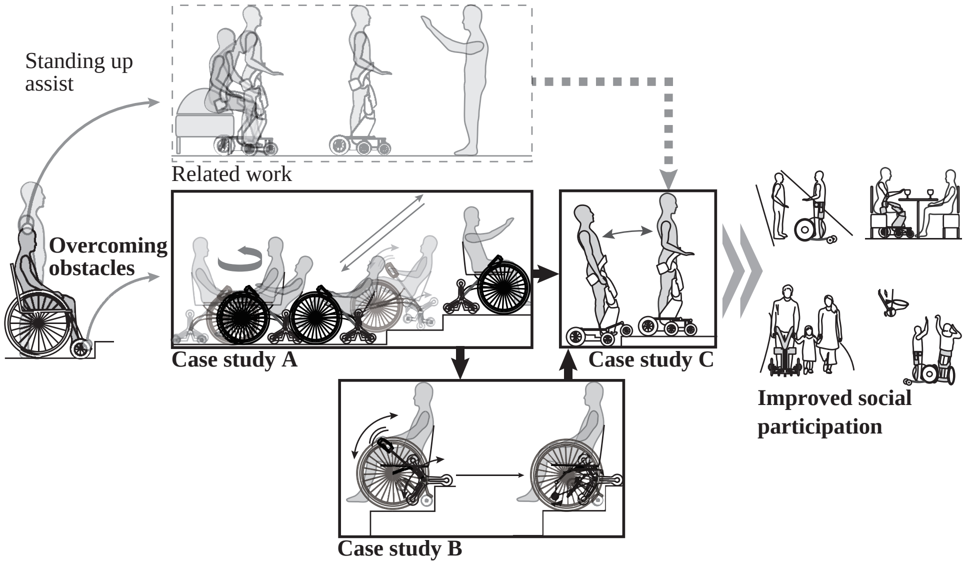


FIGURE 1.1: Overview of this research. In this research, we focus on overcoming step and stair for assistive mobility devices, especially for wheelchairs.

1. Case study A: Stair-climbing mobility device with lever propelled rotary legs
2. Case study B: Stair-climbing mobility device with an active rotary legs mechanism
3. Case study C: Standing mobility device with a passive step-climbing mechanism

1.4.1 Mechanical Power Flow between Human and Machine

First, power flow originally refers the result of the interaction between power generation, consumption, and available transmission paths in the field of electrical engineering [73, 74]. Also, concept of mechanical energy or power flow has been used in different engineering fields [75–78]. The concept of mechanical power flow is usually used to understand characteristics of target system, and effect of each component as well. In this study, I defined the mechanical power flow between human and machine as the physical interactions between mechanical components with a human including environments, which deals with energy and forces. Human is considered as not only an operator of machine, but also one of the requisite mechanical system elements to realize step/stair-climbing. Therefore, design for way of utilizing human capability such as upper body strength would determine step/stair-climbing performance, and would determine required human capability for operation.

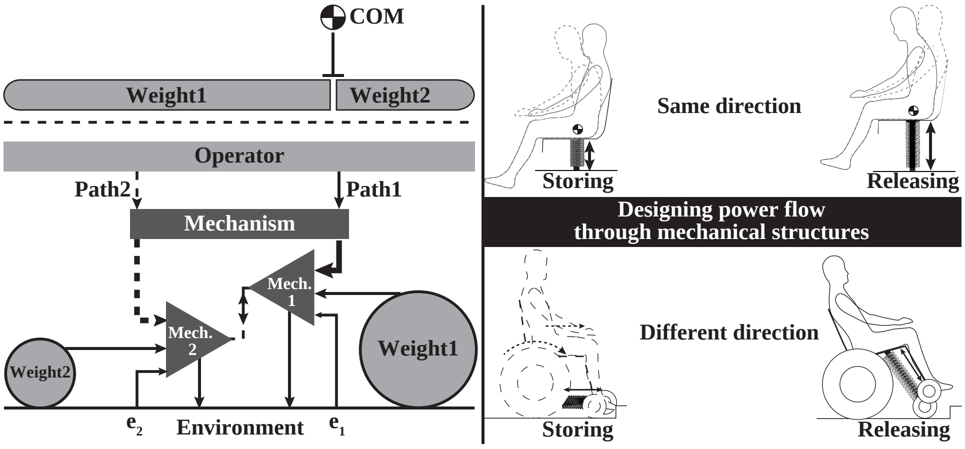


FIGURE 1.2: Fundamental concept of the proposed mechanical power flow between human and machine. e_1, and e_2 represent coefficients determined by environments such as surface conditions.

In the proposed mechanical power flow, I focus on an overall COM position of a mobility device with a human during step/stair-climbing, since the overall COM position would influence whole motion. Figure 1.2 shows the fundamental concept of the mechanical power flow in this research. Left side of the Figure 1.2 shows the relationship between the COM position and weight distribution among the mechanical components. Since mobility devices, especially wheeled mobility devices such as regular wheelchairs rely on friction forces generated at each contact points to the ground for driving forces, weight distribution by controlling the COM position would one of the key design parameters. In addition, an input point for the mobility device would also be one of the key design parameters, because a mechanical element with less distributed weight might not be able to generate enough driving force for whole motion of a mobility device. One of the examples of importance of COM position could be wheelchair propulsion. S. Sprigle et al. have reported that COM position influences wheelchair propulsion, since it impacts inertia and/or friction, and influences the amount of energy required to maneuver a wheelchair [79]. Therefore, the overall COM position with driving elements could be considerable factor.

Right side of the Figure 1.2 shows an another key aspect of the proposed mechanical power flow. Professor Sigeo Hirose, a professor emeritus at Tokyo Institute of Technology, have stated that, the essence of mechanics would be the point that it can store power flowing from input to output temporarily, it can divaricate power in an efficient manner, and it can release the power at certain timing [80]. Based on the message by the professor, I also focus on mechanical designs that can store energy at desired timing, and can release the energy to appropriate elements so that a mobility device realizes step/stair-climbing. It can be considered that not only using input from human for directly actuating mechanism, but also designing its flow could also be considerable factor.

Based on the aforementioned strategies, I designed all of step/stair-climbing mobility devices in this research.

1.5 Thesis Outlines

This paper summarizes all of my previously published papers and an additional proposed contents [81–83]. At first, the case study A, stair-climbing mobility device with lever propelled rotary legs are described in Chapter 2. In this Chapter, a stair-climbing mobility device is proposed based on a regular manual wheelchair to maintain its locomotion performance on flat surfaces. Detailed mechanical structure and its design guidelines are described. In the proposed stair-climbing mobility device, changing overall COM position plays an essential role for the proposed stair-climbing. In order to realize the enough COM position shifting, posture transition of a user is the most important design remarks. Design of not only climbing up, but also climbing down stairs are described in this Chapter. Subsequently, performance evaluations of the proposed methodology are conducted including several experiments by healthy participants, a dummy, and people with SCI.

Chapter 3 describes the case study B, stair-climbing mobility device with an active rotary legs mechanism. This Chapter also emphasizes importance of the posture transition of a user for stair-climbing. An actuator, which is called an active rotary-legs mechanism, is then proposed based on a concept of parallel elastic actuators. Distributing torque requirements between active components such as motors and passive elements such as springs is the key design. Subsequently, its design and simulation processes are described. Performance evaluations of the proposed methodology are then conducted. It includes preliminary experiments using a reduced scale prototype to verify the simulation results, and stair-climbing experiments using a full scale prototype with a dummy.

Chapter 4 describes the case study C, standing mobility device with a passive step-climbing mechanism. This Chapter describes a step-climbing methodology with standing posture utilizing COM position shifting. The mobility is designed based on a rocker-bogie mechanism whose design is often utilized for Mars rovers. The proposed mechanism is also equipped with passive components to change COM position and to store/release energy for step-climbing. Detailed working principles and design guidelines are described in this Chapter. Preliminary evaluations using a dummy were then performed to check the design feasibility.

Chapter 5 describes the discussions of all case studies to summarize an answer the aforementioned research question. Chapter 6 describes conclusions, contributions, and future directions of this research.

Chapter 2

Case Study A: Stair-Climbing Mobility Device with Lever Propelled Rotary-Legs

2.1 Purpose

The primary purpose of this case study A is to propose a stair-climbing mobility device that can climb stairs by user him/herself. We focus on exploiting human latent capabilities such as upper body strength, in combination with suitable mechanisms for human centered operation. Thus, the main support target of this case study is people with paraplegia who have healthy upper limbs. Figure 2.1 shows the concept of the proposed stair-climbing mobility device. The proposed mobility device has both planar locomotion and stair-climbing functionality, with a posture transition mechanism for combining these functions together. In addition, the proposed mobility device allows user's eye level to be lowered owing to the posture transition in order to reduce fear of falling during stair-climbing.

2.1.1 Scope of Support Target

The proposed stair-climbing mobility device would require certain amount of upper body strength for the operation. Users are required to operate the proposed mechanisms using both hands while sitting on a wheelchair. Thus, the primary support target of this case study is people with spinal cord injury up to vertebrae T12 who usually use manual wheelchairs for their daily life, because we consider that such people would have enough upper body strength for operating the proposed mechanisms. Extending the scope of the support target would be discussed based on obtained experimental results.

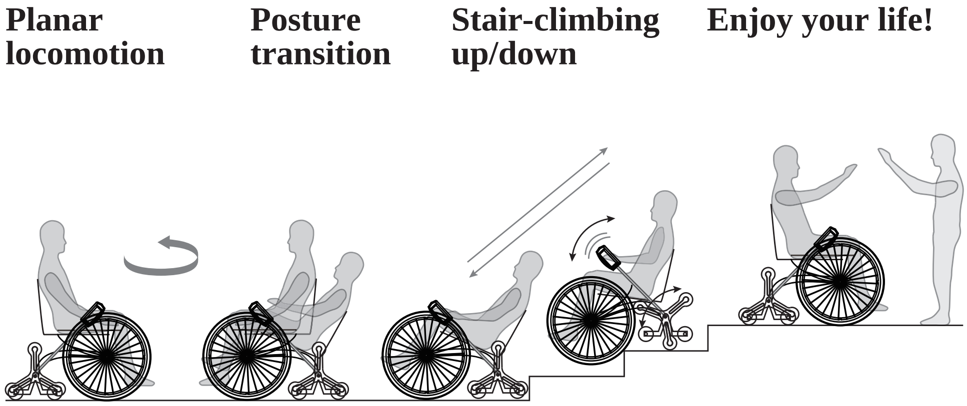


FIGURE 2.1: Concept of the case study A.

2.2 Design of the Stair-Climbing Mobility Device

An overview of the proposed stair-climbing mobility device is shown in Figure 2.2. The mobility device allows a user to perform both planar locomotion and stair-climbing by changing user's posture on the seat of the mobility device through a posture transition mechanism.

The proposed mobility device has manual wheels at the front and casters as rear wheels, which is designed based on a regular manual wheelchair. The proposed design based on a regular wheelchair would be suitable for daily usage, since wheelchair users spend most of time not for overcoming steps and stairs, but for moving on planar surfaces. As we described in Chapter 1, wheels-based stair-climbing designs usually have advantages regarding planar locomotion compared to other mechanisms such as crawler-based and leg-based designs. By this configuration, the proposed mobility device would travel as fast as a regular manual wheelchair, which can lead the users to gain their expected level of community participation [84].

The stair-climbing mechanism has a pair of mechanism designed for stair-climbing, which is called a rotary-legs mechanism, that could be driven by the user's upper body through coaxially mounted levers. The rotary-leg is a combination of a frame where three rods are positioned 120 deg apart. The influence of number of rods have been investigated in stair-climbing luggage cart, and it is concluded that the small number of rods would better because it would be simpler, smaller, lighter, and smooth movement [85]. Thus, the rotary-leg in this case study has three rods for preliminary investigations. Users can climb steps and stairs individually owing to this stair-climbing mechanism, where the rotary-legs are rotated through the coaxially mounted levers by the user. The lever mechanism is chosen to amplify the input from human, and to make the stair-climbing operation be simpler. The rotary-legs mechanism has also casters with another

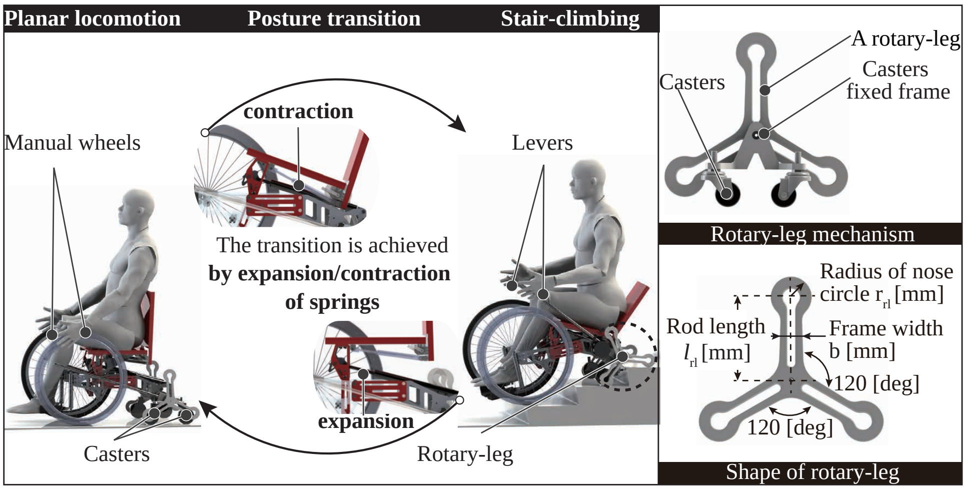


FIGURE 2.2: Outline drawing of the developed stair-climbing mobility device.

frame for planar locomotion. The casters are fixed to the another frame, and the rotational center of both frames is the same.

Users can take an appropriate posture for both planar locomotion and stair-climbing through the passive posture transition mechanism using springs. Shifting COM position of the user to an appropriate range on the mobility device would make stair-climbing more secure and stable to be performed solely using the user's upper body motion. With the posture transition, user's eye level can also be lowered, which would reduce fear of falling during stair-climbing. The posture transition from the planar locomotion posture to the stair-climbing posture can be achieved by tilting user's trunk backwards on the mobility device. This produces compression force on the springs, which causes the seat to incline backward. The opposite posture transition can be achieved by tilting user's trunk forward on the mobility device while grasping hand rim of the manual wheels. All components are passive parts, which allows for a more compact and lightweight stair-climbing mobility device.

2.2.1 Rotary-leg with Casters

Previously proposed stair-climbing mobility devices in a category of the multi-wheels mechanism often use unique wheels, which are usually called planetary wheels [62, 63]. It mainly consists of a frame where three rods are positioned 120 deg apart, one wheel at each vertex of the frame, and a mechanism for locking the wheels not to rotate freely during stair-climbing. Although the planetary wheel mechanism has both planar locomotion and stair-climbing functionalities, it tends to be large, heavy, and complicated due to the additional locking mechanism. Since we aim at proposing a compact and lightweight stair-climbing mobility device, the planetary wheel

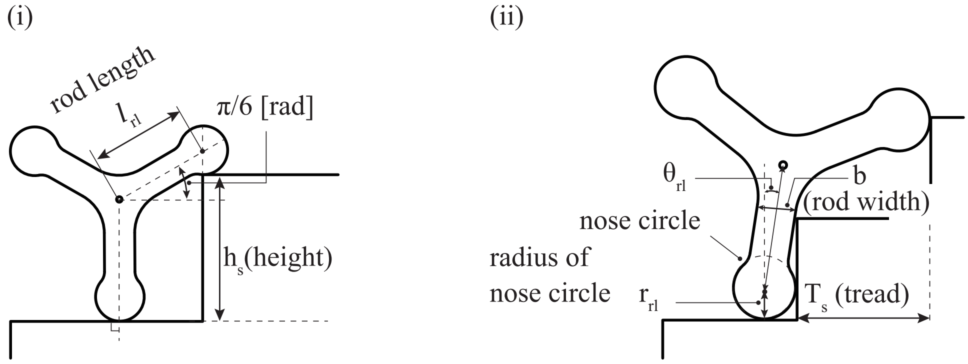


FIGURE 2.3: Conditions that the rotary-leg must satisfy in this case study.

mechanism might not be appropriate for the proposed mobility device. Therefore, the wheels are separated from the frame, and are combined with another frame in a different manner to support both the planar locomotion and stair-climbing functions together.

2.2.2 Configuration of the Rotary-leg

In order to overcome stairs with different height and tread using the proposed rotary-leg, the rod length, radius of nose circle, and rod width of the rotary-leg could be important design parameters. Specifically, the rod length can be considered as the most influential parameter, since insufficient rod length cannot fit stair configuration. Therefore, we set conditions that the rotary-leg must satisfy to ensure stair-climbing capability and safety as follows.

(i) The stair-climbing mobility device can climb each step by only rotational motion of the rotary-leg.

(ii) In order to ensure stability during stair-climbing, the rotary-leg should remain in contact with the new step after climbing one step.

These conditions for climbing stairs using the rotary motion of the rotary-leg are shown in Figure 2.3. At first, the center-to-center distance of the nose circle in vertical direction should be longer than a step height in order to climb the step. The distance reaches the maximum when the center line of the rod that is in contact with the step or the floor is perpendicular to the step. Therefore, the first condition can be derived as follows:

$$h_s < l_{rl}(1 + \sin(\frac{\pi}{6})), \tag{2.1}$$

where h_s denotes the step height, l_{rl} denotes the rod length of the rotary-leg.

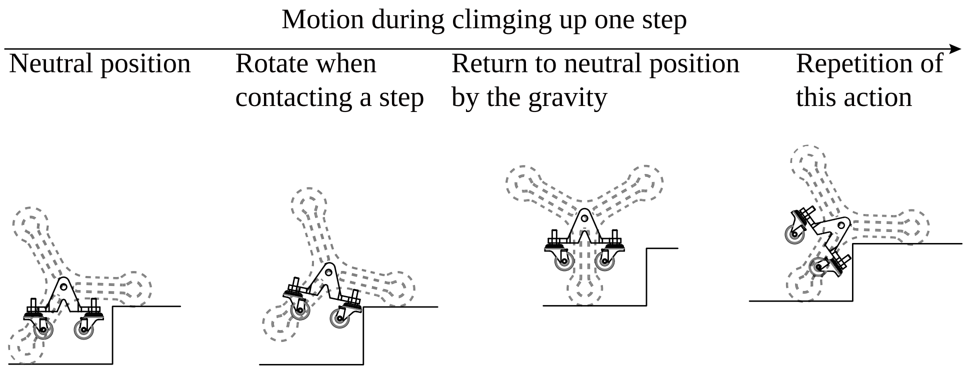


FIGURE 2.4: Motion of the rotary-leg mechanism during stair-climbing procedure.

The second condition corresponds to the fact that the maximum center-to-center distance of the nose circle in horizontal/vertical direction should be less than the length of the height of two step, and tread of one step when the rotary-leg is in contact with the side of the step.

$$l_{rl}(\sin\theta_{rl} + \cos(\frac{\pi}{6} - \theta_{rl})) < T_s, \tag{2.2}$$

$$l_{rl}(\cos\theta_{rl} + \sin(\frac{\pi}{6} - \theta_{rl})) < 2h_s, \tag{2.3}$$

$$r_{rl} - \frac{0.5b}{\cos\theta_{rl}} = (h_s - r_{rl})\tan\theta_{rl}, \tag{2.4}$$

where θ_{rl} denotes the angle between the vertical direction and the center-line of the rod that is in contact with the side of the step, T_s denotes the tread of one step, r_{rl} denotes the radius of the nose circle, and b denotes the width of the rod of the rotary-leg. Expression 2.4 is the condition for the rotary-legs not to interfere with the stair surface. We design prototypes assuming that they will be used in public spaces in Japan. According to Japanese Building Standards Law [86] and residential design guides for handling the longevity of society [87], the maximum riser is set to be 200 mm. Also, the relationship between the riser and the tread are determined as $2h_s + T_s = 650$ according to [87]. We analyze the appropriate parameters for designing the rotary-leg with the conditions mentioned above. Consequently, the rod length l_{rl}, radius of the nose circle r_{rl}, and width of the rod b are set to be $l_{rl} = 160$ mm, $r_{rl} = 40$ mm, and $b = 50$ mm, respectively for developing prototypes. Designers could conduct similar calculations for other countries according to their respective building standards and target stair configurations.

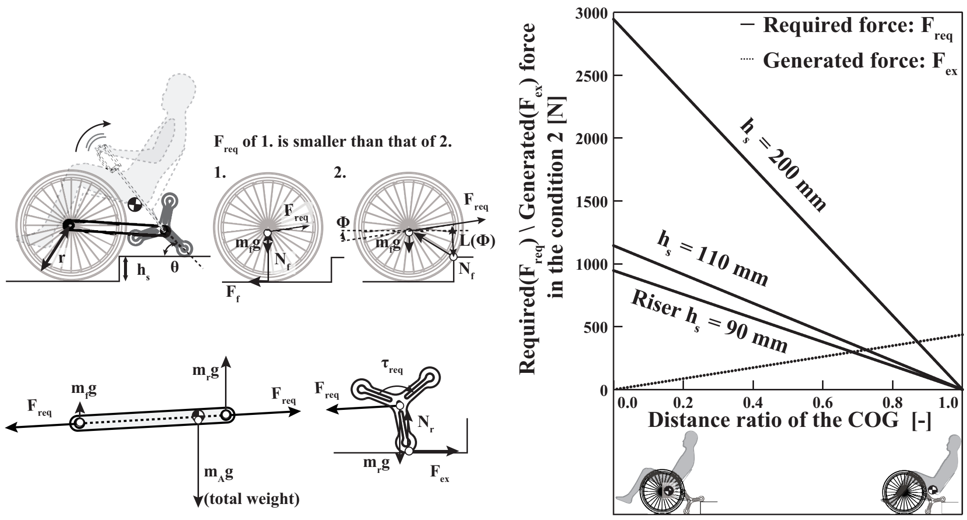


FIGURE 2.5: Relationship between generated friction force on the contact point between the rotary-legs and the stair surface, and required force for manual wheels to climb up one step. m_{mh} represents total weight of a mobility with a user. The friction coefficient between the rotary-legs and the stair surface is set to be 0.5. We derived the relationship based on the simple quasi-static free body diagram.

Motion of the Rotary-legs Mechanism during Stair-climbing

Motion of the rotary-legs mechanism during stair-climbing is shown in Figure 2.4. Frames equipped with casters on both sides have a common rotational axis with the rotary-legs. The frames are rotated freely around the axis, which allows the frames to avoid interfering with stairs. After climbing one step, the frames return to its neutral position by gravity, and allows the mobility device to have planar locomotion function.

During preliminary tests, we observed that the rotary-legs might slip during stair-climbing when the static friction coefficient between the rotary-legs and stair surface is not adequate. If the rotary-legs slip on the stair surface, it might miss a step on the stairs. Also, the rotary-legs might not be able to generate enough force to climb next step.

On the other hand, if the friction coefficient is large enough for stair-climbing, the rotary-legs can rotate while the nose circle of the rotary-legs is in contact with the stair's surface and generate required force for stair-climbing. Through this repetitive motions, the mobility device can overcome stairs just by the rotational motion of the rotary-leg.

2.2.3 Modelling for Climbing Up Stairs

In the proposed stair-climbing strategy, the rotary-leg is the driving component of the mechanism. The friction forces generated by the rotary-legs at the contact points to stair surface make the mobility device to overcome stairs. In other words, the rotary-legs pull the manual wheels through the connected frames. In this situation, there is a critical concern that the manual wheels would not be able to climb up stairs in the case that the rotary-legs cannot generate enough friction forces at the contact points between the rotary-legs and the stair surface. Therefore, investigations to clarify the key design parameters for the proposed stair-climbing are conducted in this section.

Diagrams are often used by physicists to reduce the complexity of representations and to solve physics problems. Free body diagram is one of the traditional diagrams for such purposes [88]. The free body diagram is defined by D. Rosengrant et al. as "diagrammatic representation in which one focuses only on an object of interest and on the forces exerted on it by other objects [89]." The free body diagram solves the physics problems by following three essential steps [88]:

- Construction of a free body diagram
- Graphical determination of the resultant force vector
- Finding its magnitude

In this section, we investigate essential design parameters using the free body diagram.

Figure 2.5 shows the free body diagram of the simplified proposed mobility device when climbing up stairs. A pair of manual wheels, rotary-legs, and their connection frames are constructed for the free body diagram, since they are the primary and essential mechanical components for the proposed stair-climbing. We note that the equilibrium equations are different in the stair-climbing situation, i.e. whether the manual wheels climb up one step or not. We assume that when the manual wheels start to climb up the step could be the most challenging situation, because the whole mobility device moves in the anti-gravitational direction. Thus, the required force for manual wheels at the period is derived based on the free body diagram. We also note that the rolling resistance and mass of the connected frames are neglected since they can be small enough not to influence the whole motion during the stair-climbing procedure. The goal of this investigation is to clarify key design parameters through calculations of the generated force by the rotary-legs and the required force for manual wheels to climb up one step.

First, the required force for manual wheels to climb up one step can be derived as follows:

$$F_{req} = f(m_f, h_s, r, L(\phi)) = \frac{m_f g \sqrt{h_s(2r - h_s)}}{L(\phi)}, \tag{2.5}$$

where m_f denotes the distributed mass acting on the pair of manual wheels, g denotes the gravitational acceleration, r denotes the radius of the manual wheels, h_s denotes the height of one step, $L(\phi)$ denotes the moment arm of the required force from the contact point of the manual wheels, and ϕ denotes the angle between the horizontal line and the frame that connects the manual wheels and the rotary-legs.

Second, the friction force generated by the rotary-legs at the contact point to the stair surface is then calculated as follows:

$$F_{ex} = f(\mu, m_r, \phi) = \frac{\mu m_r g}{1 - \mu \tan \phi}, \tag{2.6}$$

where m_r denotes the distributed mass acting on the pair of rotary-legs, μ denotes the maximum static friction coefficient between the rotary-legs and stair surface.

The derived forces must satisfy the following condition to achieve the proposed stair-climbing:

$$F_{ex} > F_{req}. \tag{2.7}$$

In order to clarify the key design remarks of the proposed stair-climbing methodology, ϕ is set to be 0. The required force and the generated force are then derived as follows:

$$\begin{aligned} F_{req}|_{\phi=0} &= f(m_f, h_s, r) = \frac{m_f g \sqrt{h_s(2r - h_s)}}{r - h_s}, \\ F_{ex}|_{\phi=0} &= f(\mu, m_r) = \mu m_r g. \end{aligned} \tag{2.8}$$

According to the calculation results, we consider the relevant parameters are the distributed mass acting on the pair of manual wheels m_f, radius of the manual wheels r, height of one step h_s, the maximum static friction coefficient between the rotary-legs and stair surface μ, and the distributed mass acting on the pair of rotary-legs m_r. First, the required force becomes smaller if the radius of the manual wheel r becomes larger. However, the size of the manual wheel is limited since the proposed mobility device is designed based on a regular manual wheelchair. Range of the height of one step h_s is also determined by the regulations and guidelines, which the mobility device itself can never change. In addition, the friction coefficient μ is basically limited based on the target environment, and it only affects the generated force by the rotary-legs. On the other hand, the mass acting on the pair of manual wheels m_f and rotary-legs m_r can be changed according to the position of the COM. The two parameters can be controlled by changing positions of relevant mechanical components appropriately. Therefore, we conclude that the position of COM would be the key design parameter for the proposed stair-climbing mobility device.

In the proposed stair-climbing mobility device, the most influential element for changing the position of COM could a user, since a regular wheelchair is lighter than the user. The relationship between the required and generated force can be controlled by changing the user's position on the mobility device. Therefore, the posture transition of the user is essential for the proposed stair-climbing. Figure 2.5 shows the relationship between the required force and the generated force according to the position of COM. The maximum height of one step is set to be 200 mm according to [86][87]. Figure 2.5 indicates that the mobility device cannot climb up stairs if the overall COM is located such that the required force exceeds the generated force. The distance ratio of the COM in Figure 2.5 is a ratio between the length of revolute joints of the manual wheels and the rotary-legs in the horizontal direction and the COM position from the revolute joints of the rotary-legs. In this manner, through the posture transition of the user, the overall position of COM should be shifted down and backward before starting stair-climbing. The stair-climbing can therefore be achieved.

2.2.4 Overall COM Movement during Stair-climbing

We derived that the overall position of COM plays an important role for the proposed stair-climbing methodology. With help of the posture transition of a user, the COM can be shifted to a desired range for stair-climbing. However, the overall position of the COM with respect to the revolute joint of the rotary-legs varies from moment to moment during climbing up one step by rotating the rotary-legs, which would influence whether the mobility device can climb up the step successfully and stably. Especially, the attitude of the mobility device changes from moment to moment, which affects the overall COM trajectory. Therefore, we investigate the change of overall COM position as well as attitude of the mobility device during stair-climbing in this section.

Attitude of Seating Face during Stair-Climbing

At first, an attitude of the seating face during stair-climbing is investigated by changing following key parameters:

- Wheelbase of the mobility device, which is horizontal distance between revolute joints of the manual wheels and the rotary-legs.
- Position of the rotary-legs along the vertical line from the ground.
- One step height and tread of stairs.

We consider that the parameters could be primary key parameters for changing the COM position, because how much the mobility device inclines forward/backward would be determined by the mechanical parameters. In this section, variations of the seat attitude by

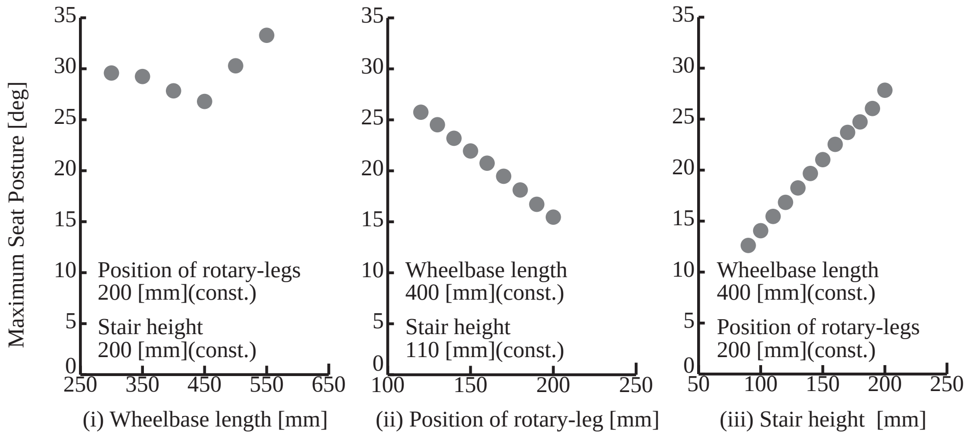


FIGURE 2.6: Simulation results of the maximum seat attitudes. The rod length, the radius or the nose circle, the rod width of the rotary-legs, and the stair tread is determined as 160 mm, 40 mm, 50 mm, and $2h_s + T_s = 650$ mentioned in Section 2.2.2.

the parameters are investigated to check whether the mobility device could perform the proposed stair-climbing. Here, the maximum seat attitudes are analyzed using a simulator (Solidworks Motion Analysis).

Figure 2.6 shows the simulation results of the maximum forward seat attitude by changing the aforementioned parameters. The seat attitude is defined as the the angle between the seating face and the horizontal plane where the forward tilting is considered positive. The seat attitude is horizontal when starting all the simulations, which the angle is 0.

First, the variation of the seat attitude reaches the local minimum at specific wheelbase. Also, the seat attitude becomes larger if the wheelbase is smaller or larger than that length. Second, the maximum seat attitude decreases with the increase of the fixed position of the rotary-legs along the vertical direction. Last, the seat attitude becomes larger with the increase of the stair height. In these simulations, the minimum seat posture was measured as 26.8 deg forward when climbing 200 mm height stair while the wheelbase is 450 mm, and the vertical fixed position of the rotary-legs is 200 mm. Therefore, the variation of the seat attitude can be as small as possible by modifying each of the mechanical parameters of the mobility device appropriately. Further, we found out guidelines for designing the posture transition mechanism how much the seat attitude must be inclined backward before stair-climbing. A stair-climbing mobility device can be designed according to these results with consideration of possible assembly of all components in practice.

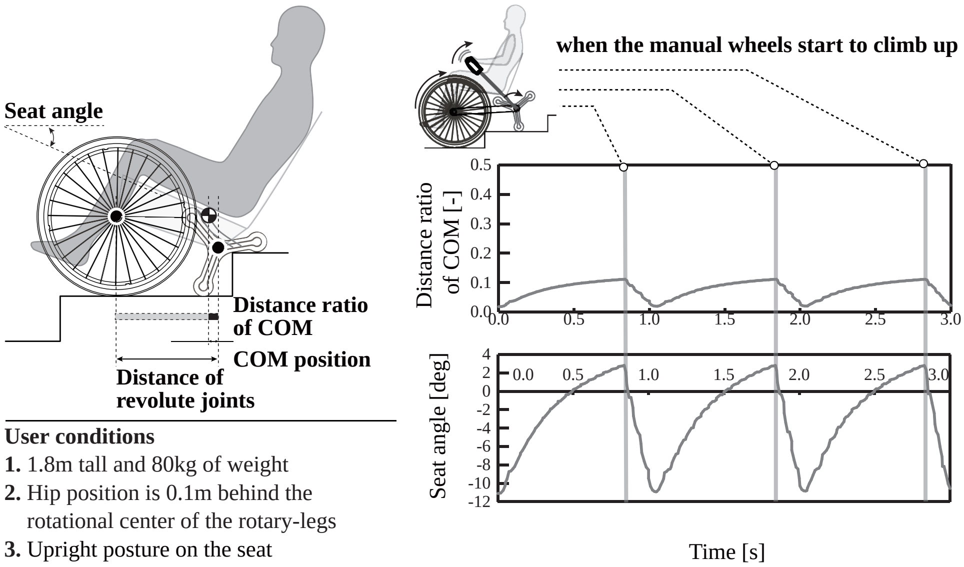


FIGURE 2.7: Simulation results of change of the overall COM position as well as the seat attitude during stair-climbing. Every simulation starts with the posture illustrated in this Figure. The manual wheels start to climb up each step on the gray lines.

2.2.5 Change of Overall COM Position during Stair-Climbing

We investigate the change of the overall COM position during stair-climbing using simulators (Solidworks Motion Analysis and Matlab). The aforementioned parameters of the mobility device that makes the change of seat attitude smaller are used in this simulations. In the current simulations, the seat attitude is inclined 25 deg backward before stair-climbing with help of the posture transition mechanism. In addition, the overall COM position of the mobility device itself is located at the middle of the wheelbase. Also, the user's weight of each body segment is estimated from the entire body mass by using Matsui's body parts mass index [90].

Figure 2.7 shows the simulation results whose step height is 200 mm, which is the maximum assumed step height in this study. The results show that the COM position becomes far from the revolute joint of the rotary-legs after starting to climb up, while it becomes closer after the manual wheels start to climb up. We also observed that the overall COM change could be within the desired range for the proposed stair-climbing.

In conclusion, the appropriate COM change through the posture transition of a user before the stair-climbing is essential for the proposed stair-climbing methodology.

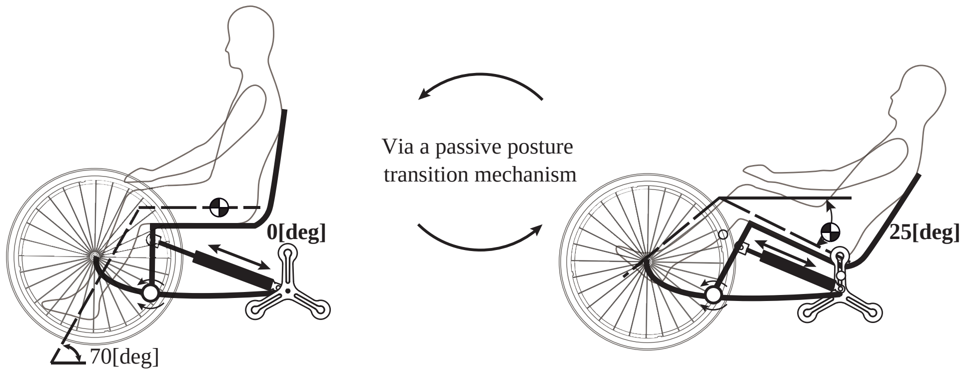


FIGURE 2.8: Postures for planar locomotion and stair-climbing. The planar locomotion posture is designed in consideration of operability of manual wheels. The stair-climbing posture is determined for ensuring stair-climbing capability as well as decreasing fear of falling.

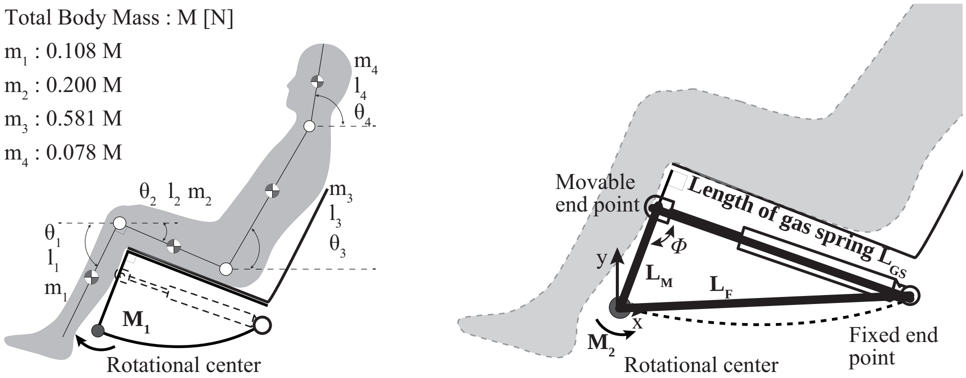
2.2.6 Method for Posture Transition of a User

We derived that the overall COM position is the key parameter for the proposed stair-climbing methodology. With the proper position of the COM, the stair-climbing could be performed by rotating the rotary-legs through coaxially mounted levers. However, the COM position for planar locomotion and the stair-climbing could be substantially different. Further, change of the seating face during stair-climbing would influence not only stair-climbing performances, but also would affect user's comfortability. Therefore, the posture transition of a user is essential for mutual transition between postures desirable for both stair-climbing and planar locomotion. In this section, we describe the posture transition methodology.

Posture Transition Model

The posture transition model between the postures for planar locomotion and stair-climbing is described here. Firstly, a user is required to move to the rear part of the mobility device so that the overall COM is located in the desired range for stair-climbing. Also as described in Section 2.2.4, the mobility device tilts forward during stair-climbing, which a user would feel as though he/she would fall down if climbing stairs with the same posture as for planar locomotion. On the other hand, if the user tilts backward farther than necessary after posture transition, they might also feel fear that they might fall. Therefore, the posture transition must allow the user to move and to tilt enough backward while considering such aspects.

According to the section 2.2.4, the maximum change of seat attitude is calculated as 26.8 deg. Here, some commercialized wheelchairs



Moment by user' s posture

Moment by springs

FIGURE 2.9: Moment generated by user's posture and by springs.

have tilting function for distributing pressures acting on user's body [91, 92]. Their maximum tilting angles are usually from 25 to 30 deg backward. In the proposed posture transition model, the seat attitude after the posture transition is set to be 25 deg backward to achieve stair-climbing and to ensure user comfortability.

The posture transition model is shown in Figure 2.8. In order to perform the proper user's posture transition with simple design, the lower end of the seat is designed to be rotated according to the relationship between moments by the user's weight and elastic components such as springs. The user is asked to control his/her upper body posture so that the relationship of the moments are changed for the posture transition. Springs are used in the proposed posture transition model not only to make the mobility device compact and lightweight, but also to execute the posture transition by only utilizing the user's upper body capabilities. The posture transition model is designed so that the moment generated by the springs exceeds that generated by the weight of the user in the posture for planar locomotion, while the moment generated by the springs falls below that generated by the weight of the user once their upper body is adequately tilted backward.

Calculation of Moment by the Posture of the User and Spring

First, we calculate the moment generated by the posture of the user during posture transition. As shown in Figure 2.9, the weight of each limb is estimated from the entire body mass by using Matsui's body parts mass index [90]. At this time, the COM of each limb is assumed to be located at the center of the limb along its length.

$$\begin{aligned} M_1 &= -\frac{1}{2}m_1 l_1 C_1 + (\frac{1}{2}m_2 + m_3 + m_4) l_2 C_2 \\ &+ (\frac{1}{2}m_3 + m_4) l_3 C_3 + \frac{1}{2}m_4 l_4 C_4, \end{aligned} \tag{2.9}$$

where m_i denotes the mass of each limb, l_i denotes the length of each limb of body segment, and C_i represents $\cos\theta_i$, where θ_i denotes the inclination of each limb.

Next, calculation of the moment by spring and selection of suitable spring are described. An algorithm is implemented to calculate moment by a spring, to select suitable spring, and its attachment position as follows.

Firstly, the limitation range to attach the spring is set so that the spring does not interfere with the mobility structure. Subsequently, all possible combinations of springs and their attachment positions are investigated. The displacement for the position is 0.01 m. The moment generated by the spring is calculated as the following equations:

$$M_2 = F L_M \sin\phi, \tag{2.10}$$

$$\phi = \cos^{-1}\frac{L_{GS}^2 + L_M^2 - L_F^2}{2L_{GS}L_M}, \tag{2.11}$$

where M_2 denotes the moment by the spring, F denotes the reaction force by the spring, ϕ denotes the angle between the link and reaction force direction of the spring, L_{GS} denotes the length of the spring, L_M denotes the length between the rotational center of the seat and the movable end, and L_F denotes the length between the rotational center of the seat and the fixed end. The mean squared error between the ideal moment and moment generated by the spring is calculated. The ideal moment corresponds to the average moment of maximum/minimum moment by changing user's upper body on the mobility device. The candidate with minimum mean squared error between the ideal moment and the calculated moment by the spring is chosen for the proposed posture transition mechanism.

2.2.7 Required Lever Propulsion Force and Friction Coefficient

The mobility device is equipped with the rotary-legs mechanism for stair-climbing. It also has the posture transition mechanism for shifting overall COM position to the desired range for stair-climbing. The remaining key design could be the lever propelled force by the user for the stair-climbing. Since the user operates the mobility device through the lever, investigation of the required force by the user

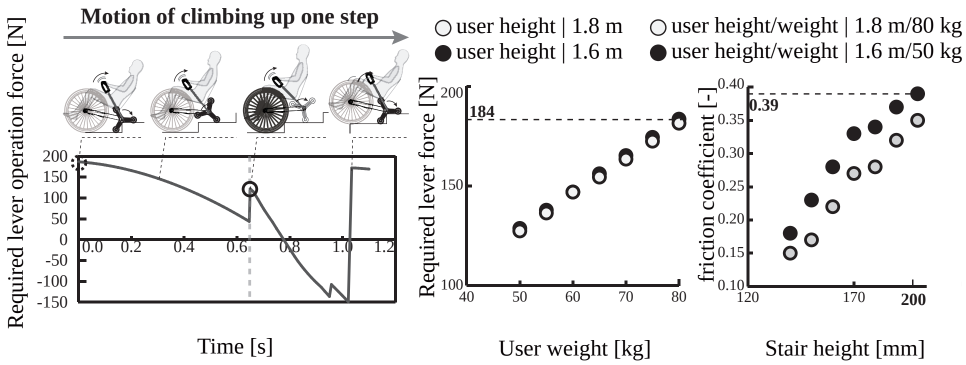


FIGURE 2.10: Simulation results of the required force and minimum required friction coefficient for stair-climbing. We set the coefficient of rolling friction of the manual wheels to be 0.03 in the simulations.

should be conducted. In addition, the required minimum friction coefficient for the stair-climbing is investigated whether the proposed method allow the user to climb stairs by rotational motion of the rotary-legs.

First, the required torque for stair-climbing is derived from Figure 2.5 as follows:

$$\tau_{req} = m_r g l_{rl} \cos\theta + F_{req}(l_{rl} \sin(\theta + \phi) + r_{rl} \cos\phi), \tag{2.12}$$

where θ denotes the rotational angle of the rotary-leg, which the θ is 0 deg when the center line of the rod that is in contact with the step or the floor is vertical to the step, and α denotes the angle between the connected frame and the center line of the rod that is in contact with the step or the floor. The require force for lever propulsion is then calculated as:

$$F_{lev} = \tau_{req}/L_{lev}, \tag{2.13}$$

where L_{lev} denotes the lever length, which the user uses to rotate the rotary-legs, and set as $L_{lev} = 0.7$ m to be reasonably operable. We note that the required force for manual wheels to move F_{req} could be changed if the manual wheels climb up stairs together with the rotary-legs or not.

The left side and middle graph of Figure 2.10 show one example of the required lever propulsion force for climbing up one step, and the required force for users with different physical parameters while climbing up stairs with 200 mm step height. The left side graph of Figure 2.10 shows the required force reaches local maximum when the beginning of stair-climbing, and when the manual wheels start to climb up the step together with the rotary-legs. We confirm that either of the forces can be maximum required force for stair-climbing. The middle graph of Figure 2.10 shows the required force becomes larger with the increase of user's body weight. For the required force for climbing down stairs, the force can be smaller than that for climbing up stairs, which has been reported in [82]. We considered that climbing downs stairs is a movement in the gravitational direction, while the climbing up stairs is a movement in the anti-gravitational direction. This results in requiring different amount of energy, and required force. Tanaka et al. [93] examined the upper body function of 53 active male paraplegics with spinal cord injury (age range: 18-54; spinal cord injury level: T4 to L4). Their investigation showed that the test group could exert sufficient force to operate the proposed lever propulsion mechanism. The mean and standard deviation of the shoulder flexion force by age are 421.8 ± 146.2 N in 20s, 446.4 ± 117.7 N in 30s, and 388.5 ± 74.6 N in 40s, which is larger than the required force for lever propelled operation during stair-climbing.

The right side of Figure 2.10 shows the required minimum friction coefficient with various stair dimensions and 2 different physical parameters of the user. The friction coefficient is calculated so that the generated force exceeds the required force for stair-climbing when the manual wheels start to climb up one step. We derived the friction coefficient since the rotary-legs must generate the most friction force for manual wheels to climb up the step. This graph indicates that the minimum required friction coefficient becomes larger with decrease of physical size of users. This is because, the COM position becomes closer to the contact point of the rotary-legs with increase of the user's physical size, especially user's weight. Also, according to researches [94, 95], the friction coefficient between a dry rubber and a dry cement is more than 1.0 [94], and rubber and vinyl is more than 0.44 [95], which is larger than the required minimum friction coefficient for the proposed stair-climbing.

Therefore, we would suggest that the proposed stair-climbing mobility device has capabilities for manual wheelchair users to climb up and down stairs by themselves.

2.2.8 Lever Propelled Direction

We simply describe possible influences by the lever propelled direction for a user in this section. Users are supposed to generate the required force for operating the levers when climbing stars. The lever propelled direction is not significant from the view point of the generated torque, since the torque generation process might not be important for the mobility. However, the lever propelled direction would be important for users, because required muscle activities could be different between pulling and pushing the lever motions.

Figure 2.11 shows the possible influences to users, especially to user's body joints by the different lever propelled direction. First, the user receives a reaction force in the opposite direction from the

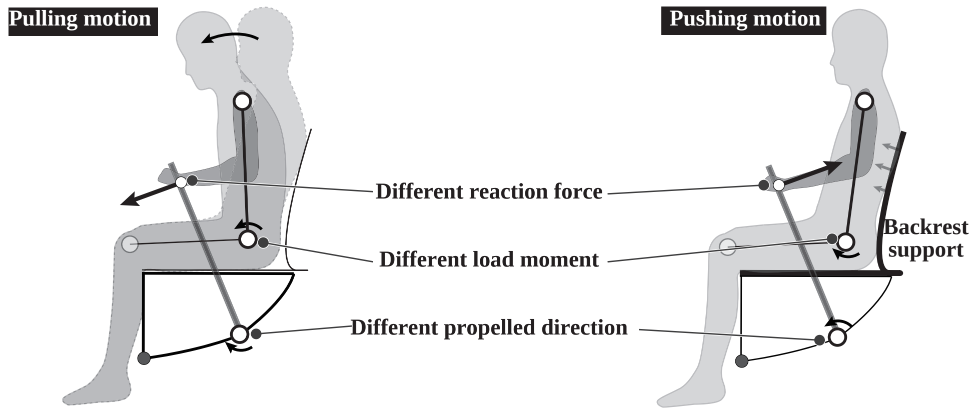


FIGURE 2.11: Influences by the different lever propelled direction during stair-climbing.

lever between pulling and pushing motions. This results in a different action to the user. When pulling the lever, the reaction force would make user's upper body to bend forward. Users are then supposed to compensate for the motion by back muscle strength, especially through activating erector muscle of spine. On the other hand, the reaction force would make user's upper body to bend backward when pushing the lever. Users are then supposed to compensate for the motion by abdominal muscles, especially through activating rectus abdominis. The proposed mobility device is designed based on a regular manual wheelchair, which has a backrest. This indicates that the user's backward motion when pushing the lever could be supported by the backrest, which would be beneficial for the target users of the proposed stair-climbing mobility device.

2.2.9 Modelling for Climbing Down Stairs

In this section, we explain fundamental methodology for climbing down stairs. During climbing up/down stairs using the proposed mobility device, even if the mobility device begin to climb down the stair accidentally, it is important that the mobility device can climb down one step at a time safely. However, it might be difficult to break the movement momentum of the mobility device due to the riser of the stair and the overall weight of the mobility device with the user, which might cause falling accidents. In order to avoid this dangerous situation, we consider that reducing rotational momentum of the rotary-legs by torque dampers, and by locking the manual wheels to the mobility device's frame. In this section, we describe the required viscosity characteristics of the torque dampers for climbing down one step at a time by considering input and output energy of the mobility device while climbing down stairs.

We first model the whole system when climbing down stairs to simplify the calculations. The whole system is illustrated in Figure

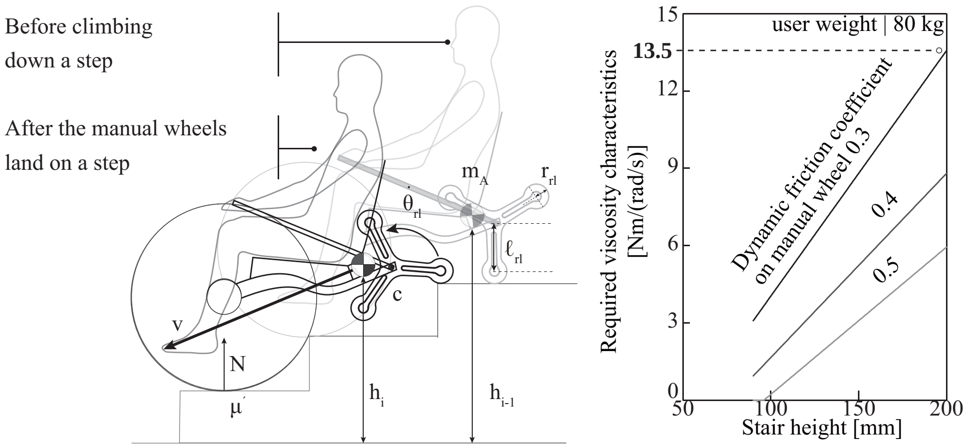


FIGURE 2.12: Energy dissipation model of the stair-climbing down procedure. During climbing down one step, energy dissipation is occurred due to both coulomb and viscous friction. We consider that the mobility device can climb down stairs if energy is dissipated sufficiently, especially by the torque dampers that is embedded in the rotary-legs mechanism.

2.12. In this model, we consider the climbing down stairs motion as going downhill whose gradient is determined according to the dimension of the stairs. We assume that the energy of the mobility device with the user before climbing down one step is only potential energy based on the vertical position of the COM of the mobility device from a base level. Next, we calculate the energy when the manual wheels land on the next step so we can determine whether the mobility device will keep climbing down stairs or not. The energy consists of kinetic energy based on the speed of the COM, and potential energy based on the vertical position of the COM from the base line. During this procedure, viscous friction caused by the torque dampers and coulomb friction due to contact between the manual wheels and a step take effect.

These energies are then derived as follows:

- energy before climbing down a step: E_b

$$m_A g h_{i-1},$$

- energy after the manual wheel lands on a step: E_s

$$m_A g h_i + 0.5 m_A v^2,$$

- dissipation energy: E_d

$$0.5 c \dot{\theta_{rl}}^2 + \int \mu' N dl,$$

where m_A denotes the overall weight of the mobility device with a user, h_i, and h_{i-1} denote the vertical position from the base line before climbing down and after the manual wheels land on the next step, respectively. v denotes the speed of the COM when the manual wheels land on the next step, c denotes the viscosity characteristics of the torque damper, $\dot{\theta_{rl}}$ denotes the angular velocity of the rotary-legs, N denotes the normal reaction force acting on the manual wheels, μ' denotes the coefficient of dynamic friction between the manual wheels and stair surface. We consider there is no input and output of energy except the energy as stated above.

The relationship between the input and output energy when climbing down one step is then derived as follows:

$$m_A g(h_{i-1} - h_i) = 0.5 m_A v^2 + 0.5 c \dot{\theta_{rl}}^2 + \int \mu' N dl. \tag{2.14}$$

We assume that, through posture transition of a user, the overall COM is located backward enough so that the speed of the COM equals the speed of the center of the rotary-legs. We also consider that the normal force acting on the manual wheels is constant and can be calculated based on the overall position of COM. We consider the maximum weight of the user is 80 kg, and the maximum riser is 200 mm.

Based on the dynamic friction acting on the front wheels and the required distance to start climbing down next step, the minimum required energy $\hat{E}$ to start climbing down is calculated as follows:

$$\hat{E} = m_A g \mu' (r_{rl}\theta_n + (r_{rl} + l_{rl}) \sin\theta_n), \tag{2.15}$$

where θ_n denotes the required rotational angle that the rotary-legs need to reach the initial situation for climbing down one step after the manual wheels land on the next step, r_{rl} denotes the radius of nose circle of the rotary-legs, l_{rl} denotes the rod length of the rotary-legs. In this study, we set r_{rl} and l_{rl} to be 0.04 m and 0.16 m to ensure proper stair-climbing up/down as we set in Section 2.2.2, and θ_n to be 12.6 deg according to parameters of the rotary-legs and the stair dimensions using Solidworks. The mobility device can climb down one step at a time without falling if the kinetic energy derived from the relationship of the input and output energy falls below the minimum required energy to start climbing down another step. In order to calculate the required viscosity characteristics of the torque damper, we used Matlab with the derived equations and assumed parameters.

Consequently, required viscosity characteristics of torque dampers are shown in Figure 2.12, which would be considered as realistic viscosity characteristics for commercial dampers. Therefore, we would suggest that the proposed stair-climbing down model could ensure safety during climbing down stairs.

2.3 Device Implementation

2.3.1 Design Guideline

The important requirements of the proposed stair-climbing mobility device are summarized as follows.

- The shape of the rotary-leg must satisfy equations $(1) - (4)$ for ensuring stair-climbing capability in public spaces in Japan. For the prototypes, according to [86, 87], the rod length l_{rl}, radius of the nose circle r_{rl}, and width of the rod b are determined as $l_{rl} = 160$ mm, $r_{rl} = 40$ mm, and $b = 50$ mm, respectively. Also, the rotary-leg with another frame which casters are fixed is proposed for making more compact, lightweight stair-climbing mobility device while keeping planar locomotion capabilities.

- The distance ratio of the overall COM position must be within the appropriate range (Figure 2.5). Also, the overall COM position must be within the range based on Figure 2.7 before starting stair-climbing procedure.

- The required force as well as necessary minimum static friction coefficient could be reasonable for the stair-climbing. For example, if a user weighting 80 kg is climbing up 200 mm height stairs with 0.7 m levers, then approximately 184 N should be exerted by using upper body when the seat angle before stair-climbing is inclined 25 deg backward, and the hip position of the user is located 0.1 m behind the rotational center of the rotary-legs. In this situation, if the minimum required static friction coefficient is larger than 0.39, the stair-climbing can be achieved.

- Lever propelled direction could affect required user's upper body capabilities, since reaction force from the lever is different, which would result in different load to users (Figure 2.11).

- To perform climbing down stairs, we consider that reducing rotational momentum of the rotary-legs by torque dampers, and locking the manual wheels to the mobility device's frame could be effective. Considering energy dissipation model of the climbing down stairs, we derived that torque dampers whose viscosity characteristics must be at least 13.5 [Nm/(rad/s)] are required in order to ensure safety during climbing down stairs (Figure 2.12).

Based on the design guidelines, 2 prototypes are developed to evaluate feasibility of the proposed stair-climbing methodology.

TABLE 2.1: Configuration of the first prototype of the stair-climbing mobility device.

Dimension [cm]	Width	73
	Length	100
	Height	65
	Wheel base	55
Total weight [kg]		24
Gas spring	FLF150-50 (KYB corporation)	
Torque damper	FDT-70A (Fuji Latex Co., LDT.)	

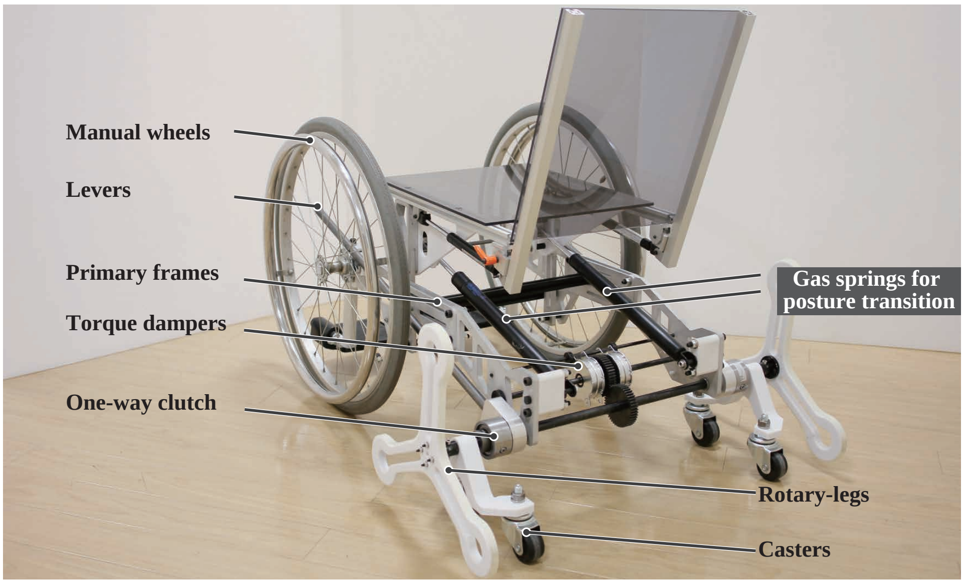


FIGURE 2.13: Overview of the developed first prototype of stair-climbing mobility device.

2.3.2 First Prototype

Figure 2.13 shows an overview of the developed first prototype of stair-climbing mobility device. The size of the manual wheel is 22 inch, and the diameter of the casters is 50 mm. Stair-climbing up and down procedures are realized by the mechanism using a pair of rotary-legs and levers for rotating the legs using user's upper body. The length of the lever is 0.7 m. The posture transition mechanism using gas springs allows a user to take suitable postures both for planar locomotion and stair-climbing. The stair-climbing mobility device is designed to be compact and lightweight to consider easy operation and vehicle installation, thus all components consist of passive parts. Table 2.1 shows the specifications of the developed prototype of stair-climbing mobility device.

The levers, which are used for stair-climbing, are connected to the rotating shaft through one-way clutches, and the rotary-legs are fixed on the shaft. The rotary-legs can rotate synchronously with

FIGURE 2.14: Overview of the developed second prototype of stair-climbing mobility device.

the levers as the user pulls them back while climbing up the stairs. The user needs to return the levers to the forward position and pull them back again to climb up continuously. However, we note that we need to reassemble the one-way clutches for climbing down the stairs which poses some inconvenience in the current prototype. The torque dampers ensure the safety of the user when climbing down stairs. We used one-way torque dampers that generate viscous friction only in climbing down direction.

Gas springs are used for the posture transition mechanism. In addition to their minimal size, these gas springs possess sufficient output strength to shift the user's position and help adjust the posture for both planar locomotion and stair-climbing. Attachment position of these springs is designed so that it allows the user to change the attitude of a seat by tilting the upper body. The developed mobility device is equipped with pair of gas springs on the right and left hand sides as shown in Figure 2.13. The transition of seat attitude between both for planar locomotion and stair-climbing is achieved by tilting the user's trunk. Tilting the trunk in the posterior direction to shift the seat attitude for stair-climbing, and in the anterior direction to shift the seat for planar locomotion.

2.3.3 Second Prototype

Figure 2.14 shows an overview of the second prototype of stair-climbing mobility device. The prototype is developed for stair-climbing experiments with end users. It is equipped with same size of manual wheels, rotary-legs, and levers. The primary difference compared to the first prototype is lever propulsion direction for climbing up stairs.

In the second prototype, users are asked to push the lever to climb up the stairs. A pair of gear is installed to change the lever propelled direction. The reduction ratio is approximately 1.7. Thus, users can operate the levers with less forces compared to the first prototype. It is worthy to note that the second prototype is developed according to suggestions from clinical professionals after several stair-climbing experiments by healthy participants using the first prototype. In addition to this, a ratchet mechanism is also installed into the second prototype for safety consideration. The second prototype can maintain its posture even if users accidentally lose their grip. Further, the rotary-leg is equipped with the rubber to reduce impact when the rotary-leg contact to stairs.

2.4 Performance Evaluations

I conducted several experiments to verify the feasibility of the proposed methodology for the stair-climbing mobility device. The first prototype was mainly used for preliminary experiments by healthy participants, while the second prototype was primarily used for end-user study.

2.4.1 Planar Locomotion Performance

First, planar locomotion performance was evaluated using the first prototype. The purpose of this experiment was to check its planar locomotion performance while being equipped with the stair-climbing mechanisms. We observed whether the prototype maintains the locomotion performance or not.

Experimental Procedure

The experiment for the planar locomotion was investigated indoors with a healthy participant (age 22, 173 cm, 65 kg). The participant was asked to return to an initial position by going through certain points.

Results

Figure 2.15 shows an image sequence of the experiment for the planar locomotion. It is confirmed from the image sequence that the participant could go straight, turn right, turn in place, and turn left with the developed prototype by maneuvering the manual wheels at the front. Thus, the experimental result indicates that the prototype has planar locomotion capabilities similar to a regular manual wheelchair.

FIGURE 2.15: Experimental result of the planar locomotion performance.

2.4.2 Posture Transition Performance

The experiment for posture transition was then performed. The purpose of the experiment was to observe whether the user's posture can be changed by tilting user's upper body on the prototype.

Experimental Procedure

The experiment was performed with the same participant for the planar locomotion using the first prototype. The participant was asked to change his upper body posture on the prototype so the posture transition mechanism using gas springs can be worked, and the participant can take postures for both planar locomotion and stair-climbing.

Results

Figure 2.16 shows an image sequence of the experiment for the posture transition. It is confirmed from the image sequence that the participant could smoothly change his posture by tilting his upper body backward while pushing the primary frames of the prototype, and could take the desired posture for stair-climbing. It took approximately 5 seconds. Further, the participant could also take posture for planar locomotion smoothly by tilting his upper body forward while grasping the hand rim of the prototype, which tool approximately 3 seconds.

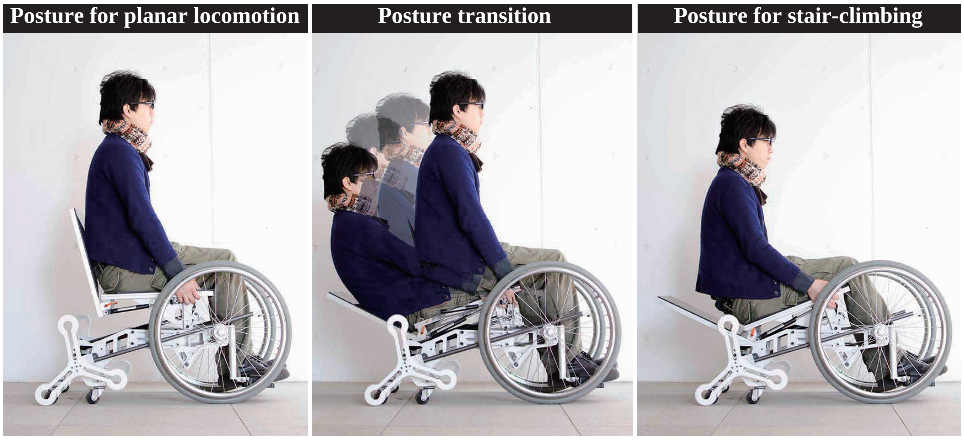


FIGURE 2.16: Experimental result of the posture transition performance.

2.4.3 Stair-Climbing Up Performances

Next, experiments for stair-climbing up were performed to verify feasibility of the proposed stair-climbing methodology. The purpose of the experiment was to verify whether users could climb up stairs using the posture transition mechanism and lever propelled rotary-legs.

Experimental Procedure

The first experiment was performed outdoor with the same participant using the first prototype. In this experiment, the participant was asked to move in front of the stair by maneuvering the manual wheels. The participant was then asked to change his posture for stair-climbing using the posture transition mechanism, and to start stair-climbing procedure. The riser and the tread of the stair were 95 mm and 700 mm, respectively, for the preliminary investigations.

Second, another stair-climbing experiment was performed indoor with the same participant using the first prototype. In this experiment, the participant was asked to climb a stair with higher step height. Before starting the experiment, the seat components were modified so the user could take a desired position for stair-climbing. The riser and the tread of the stair were 160 mm and 300 mm, respectively.

Results

Figure 2.17 shows an image sequence of the experiment for stair-climbing up outdoor. It is confirmed from the image sequence that the participant could move to the target stair, could take an appropriate posture for stair-climbing, and could climb up the stair by user

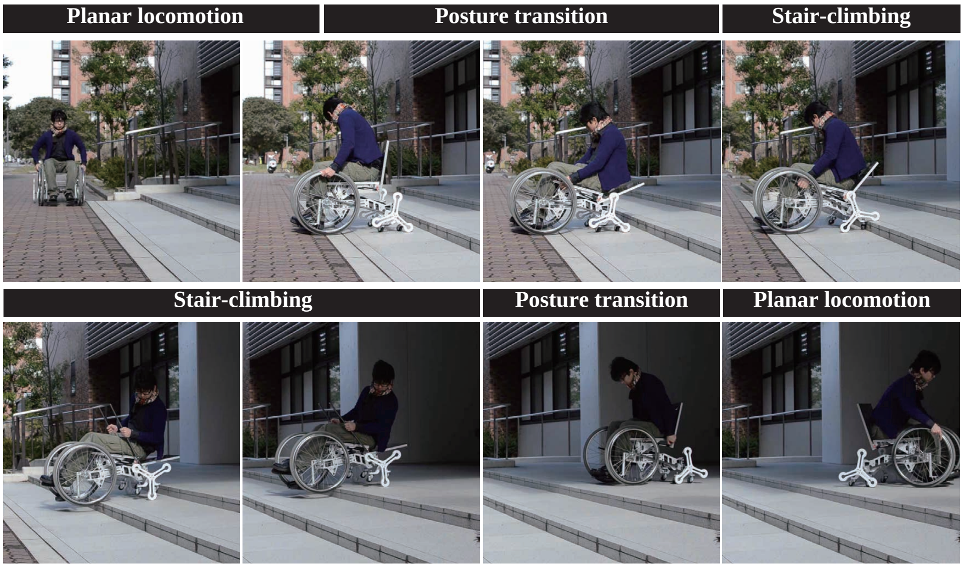


FIGURE 2.17: Experimental result of the climbing up the stair outdoor.

himself using the posture transition and the lever propelled rotary-legs. After climbing the stair, user could also take a posture for planar locomotion, and could move around. In this experiment, the participant reported that he could pull the levers without bracing his feet during stair-climbing. However, it is observed that the rotary-legs slightly slipped when manual wheels started to climb each step.

Figure 2.18 shows the experimental result for stair-climbing up using the stair whose riser was higher than the previous experiment. In this experiment, the participant could climb the stair using the lever propelled rotary-legs with the desired posture transition. The participant could climb each step for approximately 6 seconds. We note that the rotary-legs did not slip in this experiment.

2.4.4 Stair-Climbing Down Performance

Experiment for climbing down stairs was performed with the same participant using the first prototype. The purpose of the experiment was to verify the feasibility of the proposed stair-climbing down methodology using torque dampers.

Experimental Procedure

I reassembled the one-way clutches before the experiment began such that the user could climb down the stair using the lever propulsion mechanism. The prototype was also equipped with 4 torque dampers rated at 11 Nm each (total viscosity characteristics is approximately 21.0 [Nm/(rad/s)] when rotational speed is 20 rpm) to ensure user

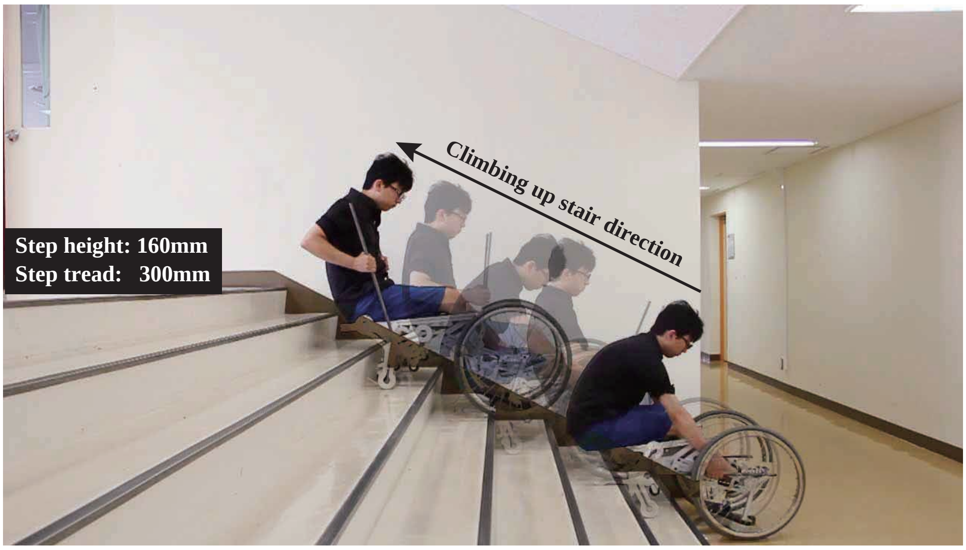


FIGURE 2.18: Experimental result of the climbing up the stair indoor.

safety. The manual wheels were locked not to be rotated for safety consideration.

Results

Figure 2.19 shows an image sequence of the experiment for the climbing down the stair. It is confirmed that the developed prototype could successfully climb down the stair through the proposed damper mechanism without any falling accidents. In addition, the impact during landing was small enough to feel comfortable for the participant. Moreover, the prototype did not fall down the stair because of sufficient backward shifting of the overall COM position through the posture transition, the torque dampers, and the locked manual wheels. It is noted that the manual wheels slipped during the experiment instead of rotating since they were locked.

2.4.5 Required Force for Lever Propelled Operation

Experiment for measuring the required force for lever propelled operation using the first prototype was conducted. The purpose of the experiment was to check whether the simulation for the required force was reasonable or not.

Experimental Procedure

A dummy (Hybrid-III5th Percentile Female Dummy, JASTI Co., LTD.) whose weight is modified to 60 kg was used for the experiment. The riser and the tread of the stair were 125 mm and 300 mm, respectively in this experiment. The dummy was placed on the prototype

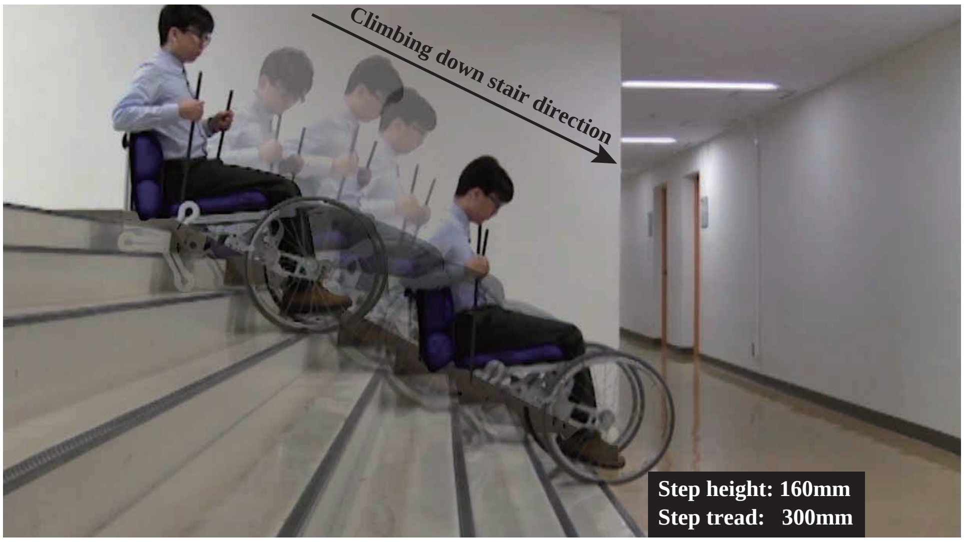


FIGURE 2.19: Experimental result of the climbing down the stair indoor.

such that the hip position is located 0.1 m behind the rotational center of the rotary-legs. The right and left side lever were coupled with a bar, where the lever length is 0.7 m. I pulled the bar in the direction perpendicular to the lever using a digital force gauge (ZP-1000N, IMADA CO., LTD.) to measure the required force.

Results

Figure 2.20 shows the measured force for climbing up the stair. First, the measured force reached local maximum when starting to climb up the stair, and when the manual wheels start to climb up each step by rotating the rotary-legs, which is same characteristics as we described in Section 2.2.7. The measured force decreased as the rotary-legs rotated after reaching the local maximum. We also calculated the force using the simulations shown as dotted line in Figure 2.20. Figure 2.20 shows a good accordance between the measured and calculated forces.

2.4.6 Lever Propelled Direction

We conducted an experiment for measuring muscle activities with different lever propelled direction. The purpose of this experiment is to evaluate the influences by the different lever propelled direction to users.

Experimental Procedure

A healthy participant (age 27 years, 173 cm, 65 kg) participated in the experiment. First, the participant climbed up 2 steps whose riser is

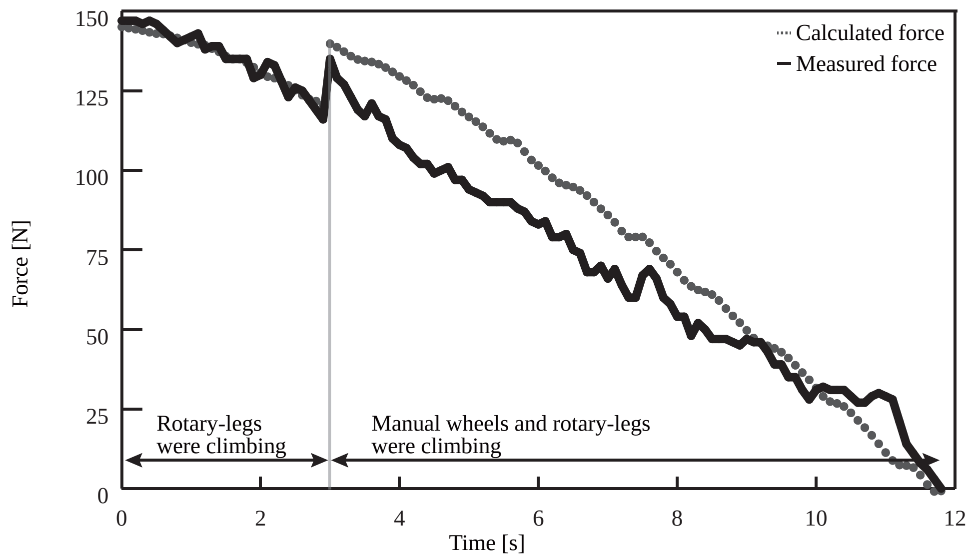


FIGURE 2.20: Experimental result of the measured force for lever propelled operation.

110 cm with the second prototype, which the participant pulled the lever for the stair-climbing. After the stair-climbing, the lever propelled direction was changed by the gear train whose reduction ratio is approximately 1.7. The participant then climbed the same 2 steps by pushing the lever. During the experiments, the participant was equipped with wireless Electromyography (EMG) sensors (Trigno Lab, Delsys, USA) on the biceps, triceps, deltoid anterior/posterior, trapezius, infraspinatus, erector spinae (T6,10,12), gluteus maximus, pectoralis major, and rectus abdominis (T6,8,10). The 14 EMG sensors were put on the right side of the participant's body. Measured EMG data were band-pass filtered, rectified, root mean squared by a moving window of 300 ms width, low-pass filtered, and averaged.

Results

Figure 2.21 shows the experimental results regarding muscle activities with the different lever propelled direction during climbing up stairs. This result shows that the different muscles were primarily activated based on the lever propelled direction. For example, biceps, deltoid posterior, and trapezius were mainly activated for pulling the lever. On the other hand, triceps, and deltoid anterior were mainly activated for pushing the lever. Furthermore, the result indicates that more back/shoulder muscles (especially erector spinae T10/trapezius) would be required for pulling the lever motion compared to the pushing lever motion during stair-climbing. We note that the participant might be required for less upper body strength because of the gear train when pushing the lever motion.

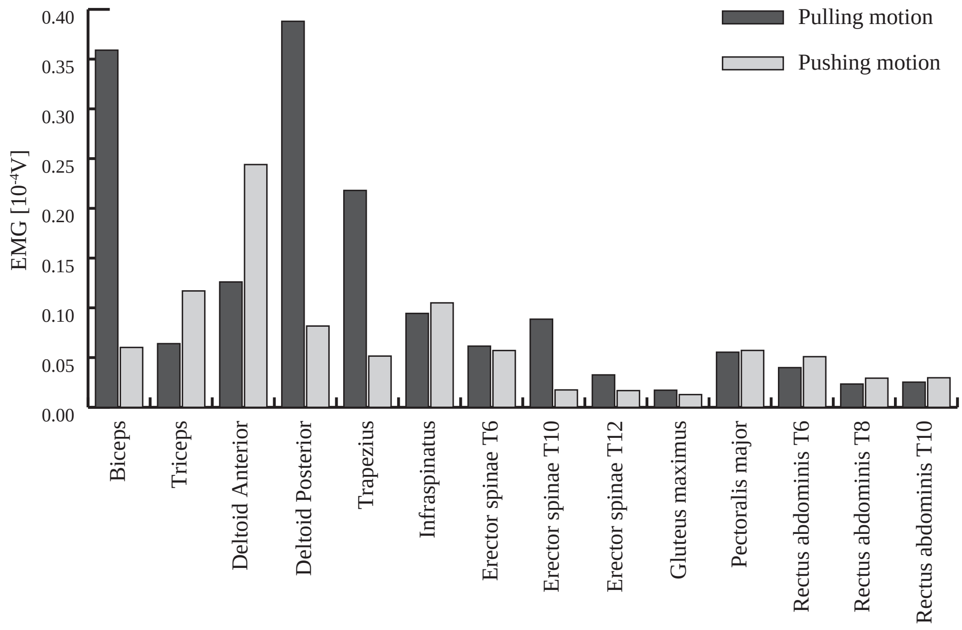


FIGURE 2.21: Experimental result of the measured EMG during pulling and pushing the lever for stair-climbing.

2.5 End-User Study

Experiments for climbing up stairs by end users were conducted in collaboration with University of Tsukuba hospital. We recruited 3 manual wheelchair users as test-pilot volunteers to evaluate the feasibility of the proposed stair-climbing methodology. They are people with SCI vertebrae T11, T9, and T4, respectively. All participants participated in the experiments with the informed consent of them, and all procedures were approved for by the ethics committee in the University of Tsukuba.

Experimental Procedure

The second prototype was used for the experiments. All participants were asked to operate the lever to climb up stairs. Participants were asked to push the levers in this stair-climbing experiment. The prototype took the stair-climbing form before starting the experiment. We used 2 different types of stairs. One is that the riser and the tread were 125 mm and 300 mm, respectively, and the other is that 110 mm and 300 mm, respectively. All participants were asked to climb the former stair. In addition, the person with SCI vertebrae T11 was also asked to climb the latter stair for investigating the feasibility of the proposed stair-climbing methodology.

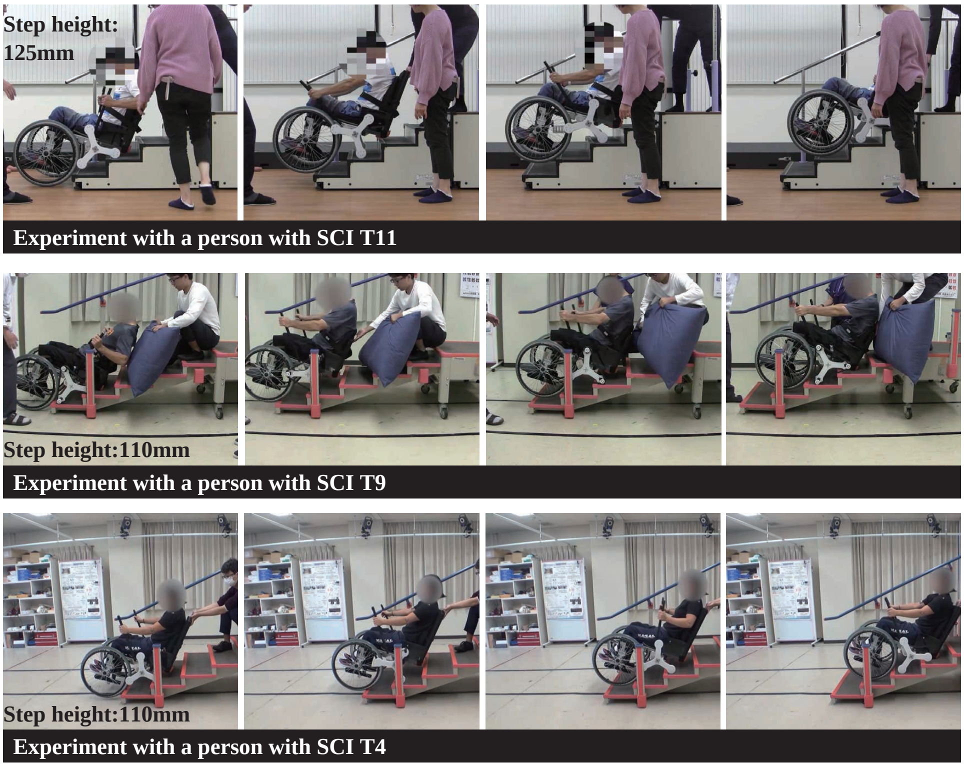


FIGURE 2.22: Experimental results of the stair-climbing up by the end users.

Results

Figure 2.22 shows the image sequence of the experiments for climbing up the stairs. We confirmed that all participants could climb up the stairs using the proposed posture transition mechanism and the lever propelled rotary-legs by user themselves. In addition, they reported that they could operate the lever operation without excess upper body strength. However, they also reported that they felt fear when the rotary-legs about to land on the next step, when the prototype was slightly going down in the vertical direction.

Chapter 3

Case Study B: Stair-Climbing Mobility Device with an Active Rotary Legs Mechanism

3.1 Background

As we mentioned in Chapter 1, previously developed stair-climbing mobility devices often consume much energy when climbing stairs compared to moving on two-dimensional surfaces. Since wheelchair users spend most of times on the surfaces, stair-climbing mobility devices are supposed to maintain planar locomotion capabilities in terms of energy consumption. In other words, energy consumption during stair-climbing must be as almost same as that during planar locomotion.

In Chapter 2, we proposed a stair-climbing mobility device with lever propelled rotary-legs using user's upper body strength. It is compact, lightweight, and does not required any powered mechanisms owing to the shifting of overall COM position to the desired range through user's posture transition. In the previously developed stair-climbing design, a user is shifted to close the rotational point of the rotary-legs through the posture transition of the user, which contributes to reduce the torque requirements for the stair-climbing, and thus enables the lever propelled rotary-legs to be operated using only the human upper body strength.

The purpose of the case study B is to propose a powered mechanism to actuate the rotary-legs which consumes as almost same energy as a regular powered wheelchair. In this case study B, a novel active mechanism is proposed based on the previous stair-climbing design, named the active rotary-legs mechanism, to actuate the rotary-legs. Instead of directly actuating the rotary-legs using motors, the proposed mechanism preserves the advantages of the previous design by replacing the lever propelling action by a user. The proposed mechanism combines the appropriate passive components with motors, such that the mechanism can be small, compact and consume lower energy for climbing up and down stairs. In addition, the mechanism is designed to still potentially allow a user to control the rotary-legs using the lever propelling action manually. A

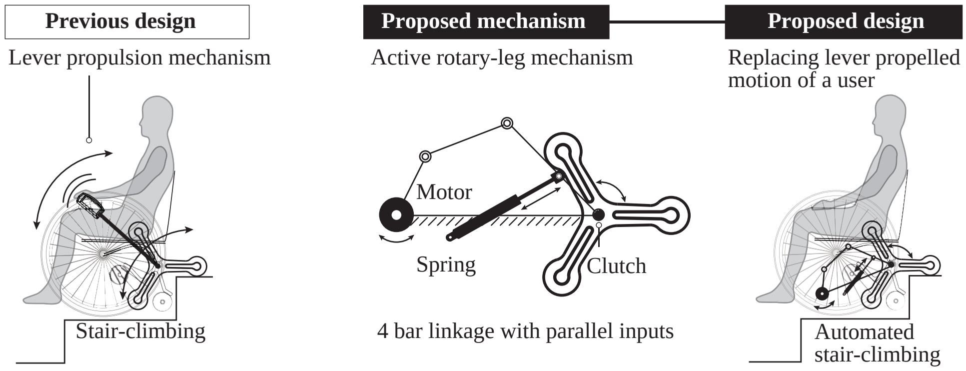


FIGURE 3.1: Concept of the case study B.

detailed design of the active rotary-legs mechanism is described and the simulations as well as preliminary experiments are performed to verify the feasibility of our design.

3.1.1 Scope of Support Target

The primary support target of this case study extends to people who do not possess enough upper body strength to operate the previously developed stair-climbing up and down mobility device independently. The scope of the support target includes not only people with more severe spinal cord injury above vertebrae T12, but also people who do not have enough upper body strength such as elderly persons.

3.2 Active Rotary-Legs Mechanism

In the case study A, participants for the stair-climbing could operate the lever to actuate the rotary-legs for climbing stairs. The proposed active rotary-legs mechanism replaces the original lever propelled operation by a user. The proposed mechanism must rotate the rotary-legs at certain angular velocity. Therefore, we introduce the proposed mechanism based on the results of the previous stair-climbing experiments. In this case study, the maximum user weight and height of one step is set to be 80 kg, and 200 mm, respectively, which are the same conditions as the case study A.

We then determine the requirements of the mechanism as follows.

- The maximum required torque is approximately 130 Nm.
- Climbing one step took around 6 s in the previous stair-climbing by the healthy participant. Thus, the proposed mechanism must enable a user to climb one step within the almost same time.
- The stair-climbing design does not require any position and speed control for the rotary-legs.

- The proposed mechanism can also potentially allow a user to control the rotary-legs using the lever propelling action manually towards power-assisted version.

In order to satisfy the requirements, we propose a 4 bar linkage mechanism combined with motors and springs. Figure 3.1 shows the concept of the proposed mechanism. First, a mechanism for amplifying input torque is required. The 4 bar linkage mechanism has capability for amplifying the input torque sufficiently for stair-climbing. In this mechanism, movement of the output link can be utilized for rotating the rotary-legs. However, the transfer ratio between the input and output link would be large, because the required torque is approximately 130 Nm. This would make the movement angle of the output link becomes smaller if the transfer ratio becomes larger. The required time for climbing one step might exceed the target time. The important point is that the transfer ratio tends to become larger, since only the input link by a motor should exert the whole required torque. Therefore, reducing the torque requirement for the motor could be one of the suitable solutions to reduce the transfer ratio.

Recently, series elastic actuators (SEAs) and parallel elastic actuators (PEAs) have been proposed to reduce the torque requirement [96–99]. These actuators consist of active components, such as motors, and passive components, such as springs. Especially, PEAs can reduce the peak torque, energy requirements, and power consumption of active components since the torque generated by whole mechanism can be distributed between the active and passive components. The passive components can provide the portion of the required torque that can lower the required torque by active one. In the proposed mechanism, this design can also reduce the transfer ratio between the input and the output link of the 4 bar linkage. It could be considered that this might contribute to satisfy our target time as well as the required torque. Therefore, the 4 bar linkage mechanism combined with motors and springs are proposed. The mechanism consists of a motor as an active component, and a spring as a passive component which possess a required force enough for the proposed mechanism. These components are combined with the 4 bar linkage.

3.2.1 Working Principle

The working principle of the proposed mechanism is shown in Figure 3.2. The mechanism has two different phases. The first phase is one where the motors and the springs exert torques in parallel (right side in Figure 3.2). The second phase is one where the motors compress the springs for the next rotation (left side in Figure 3.2). Each phase works alternately when the mechanism takes singular points. Furthermore, when the actuator is in the phase demonstrated on the right side in Figure 3.2, the torque can be utilized for rotating the

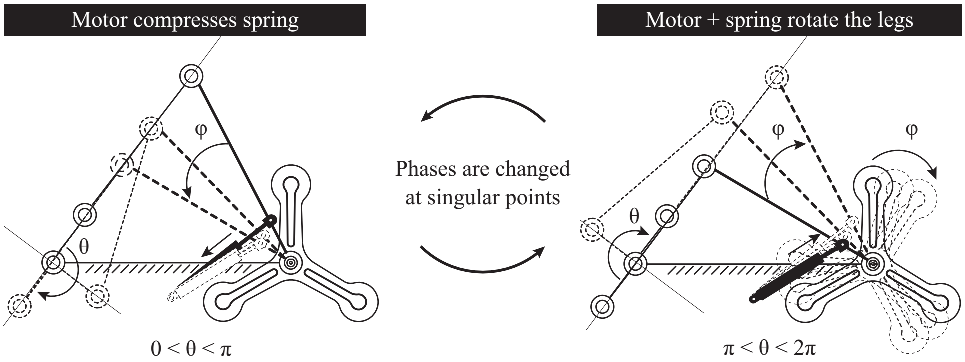


FIGURE 3.2: Working principle of the proposed mechanism.

rotary-legs. Therefore, one-way clutches are required for transmitting the generated torque with the proper timing. The output link of the 4 bar linkage is connected to the one-way clutch. The one-way clutch is subsequently connected to the rotating shaft of the rotary-legs so that the generated torque by the mechanism is transmitted to the rotary-legs only when the motors and the springs exert torques in parallel (right side in Figure 3.2). The angular displacement ϕ is determined based on the length of each link, which is equal to the rotational angle of the rotary-legs over one motor cycle.

The whole torque of the mechanism consists of the torque generated by the motor through the linkage and by the spring. Thus, the torques must satisfy the following equation:

$$\tau_{req} < \tau_m + \tau_s, \tag{3.1}$$

where τ_{req} denotes the required torque for the stair-climbing, τ_m denotes the output torque by the motor through the linkage, τ_s denotes the output torque by the spring. These variables are defined on the output link of the 4 bar linkage. The output torque by the motor through the linkage must exceed that by the spring to compress it after rotating the rotary-legs as follows:

$$\tau_m > \tau_s. \tag{3.2}$$

By distributing the required torque for stair-climbing between the motors and the springs using the 4 bar linkage, the requirements could be satisfied. In this case study, it is assumed that distributing half of the required torque to the torque by the spring could contribute to reduce the required motor torque and power consumption. Therefore, considering hysteresis of the spring, the torque generated by the motor τ_m, and the torque generated by the springs τ_s are set to be 84 [Nm] and 60 Nm, respectively.

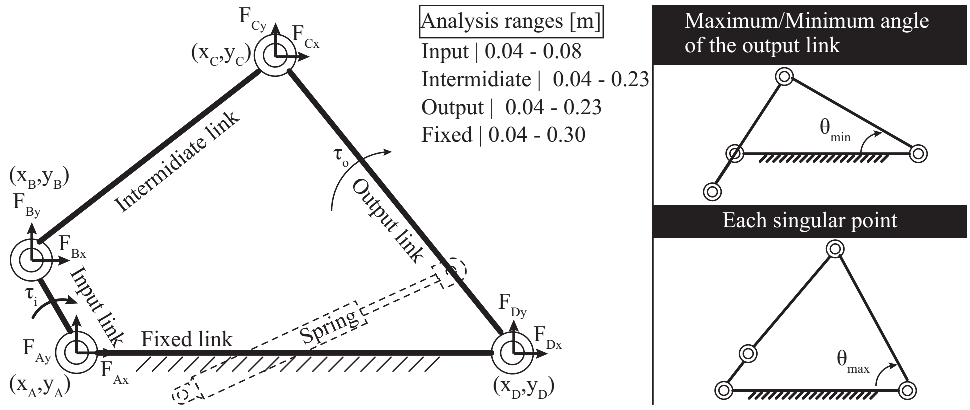


FIGURE 3.3: Geometric definition for statistical analysis of the 4 bar linkage mechanism.

3.2.2 4 Bar Linkage Mechanism

First, characteristics of the 4 bar linkage mechanism is discussed as shown in Figure 3.3. The required torque for the stair-climbing is already set to be 130 Nm. Subsequently, the required input torque by the motor is calculated. Also, the angular displacement of the output link is calculated since the angular velocity of the output link influences the required time. The required input torque and the angular displacement are determined based on the length of each link. Therefore, the desired characteristics can be obtained by adjusting each link length. However, the whole size of the proposed mechanism must be limited since the mechanism is supposed to be implemented in the previously developed stair-climbing mobility device. In order to satisfy the conditions, an algorithm is implemented to choose the appropriate length of each link so that the whole mechanism can satisfy the aforementioned requirements. In the simulation by the algorithm, the length of each link with minimum required input torque, and relatively large angular displacement of the output link is chosen for the proposed active rotary-legs mechanism.

1. First, the minimum/maximum link lengths are set based on the structure of the previously developed stair-climbing mobility device as shown in Figure 3.3. As an initial phase for the iterative process, each link length is set to be at the minimum value.

2. Subsequently, the trajectories of all links and the angular displacement of the output link are calculated over one motor cycle. The required input torque and the forces acting on each link are subsequently calculated to check if the link length is

suitable based on the free body diagram of the linkage mechanism as follows.

$$A\boldsymbol{f} = \boldsymbol{b} \tag{3.3}$$

where

$$\begin{aligned}
\boldsymbol{f} &= (F_{Ax}\ F_{Ay}\ F_{Bx}\ F_{By}\ F_{Cx}\ F_{Cy}\ F_{Dx}\ F_{Dy}\ \tau_i)^{\mathrm{T}} \\
\boldsymbol{b} &= (0\,0\,0\,0\,0\,0\,0\,0\,\tau_o)^{\mathrm{T}} \\
A &=
\end{aligned}$$

$$\begin{bmatrix}
1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -y_{B-A} & -x_{B-A} & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -y_{C-B} & -x_{C-B} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & -y_{C-D} & -x_{C-D} & 0 & 0 & 0
\end{bmatrix}$$

where from F_{Ax} to F_{Dy} denote the force acting on each pair of the linkage mechanism along the x and y coordinate axes, respectively; τ_i denotes the input torque by a motor; τ_o denotes the output torque of the linkage mechanism; and x_{i-j} and y_{i-j} represent $x_i - x_j$ and $y_i - y_j$, respectively, where x_i, x_j, y_i, y_j denote the x and y positions of the pairs.

3. The algorithm continues the process 2) with all the combinations of the link lengths. The displacement of each link length is 0.01 [m]. After finishing the entire iterative process, the linkage mechanism with the smallest required input torque, larger angular displacement of the output link, and smaller force acting on the input link is selected for the proposed active rotary-legs mechanism.

The required torque characteristics of the motor and the selected linkage structure are described in Section 3.3.1.

3.2.3 Design Guideline for Selecting Spring

Here, the design guideline for selecting the spring is described. First, gas spring is selected for the proposed mechanism since it can exert the required force with compact size compared to other springs such as regular compression springs or torsion springs. In this case study, the attachment position of the gas spring is also strictly limited to satisfy the aforementioned requirements. Therefore, an algorithm is implemented to choose a suitable gas spring and its attachment

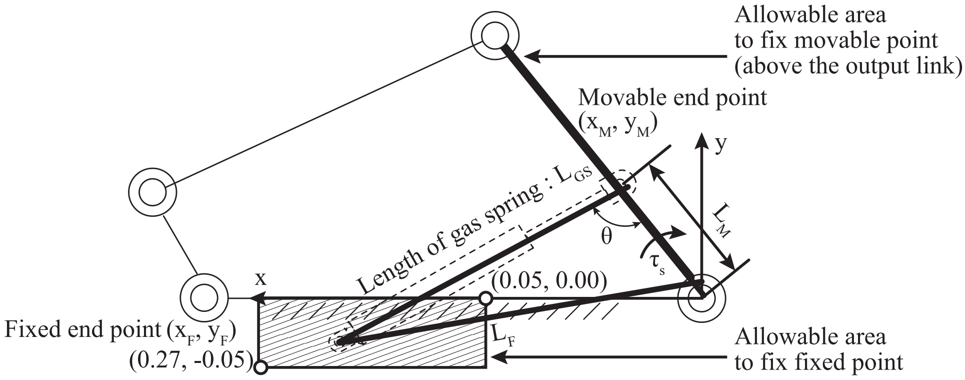


FIGURE 3.4: Geometric definition for designing the arrangement of spring.

position such that the torque by the spring exceeds 60 Nm while the spring rotates the rotary-legs as follows.

1. First, the desired range for attaching a gas spring is set based on the structure of the mobility device as shown in Figure 3.4. As an initial phase for the iterative process, the movable and fixed positions are set at one of the points within the allowable areas.

2. Subsequently, the gas spring is selected if it satisfies following conditions:

   - The maximum/minimum length of a gas spring is longer/shorter than the length required for the movement of the output link.

3. Finally, the torque generated by a gas spring is calculated as follows.

$$\tau_s = F L_M \sin\theta, \tag{3.4}$$

$$\theta = \cos^{-1}\frac{L_{GS}^2 + L_M^2 - L_F^2}{2L_{GS}L_M}, \tag{3.5}$$

where τ_s denotes the torque generated by a gas spring, F denotes the reaction force of a gas spring, L_M denotes the distance between the rotational center of the rotary-legs and the movable end, L_F denotes the distance between the rotational center of the rotary-legs and the fixed end, L_{GS} denotes the length of the gas spring, and θ denotes the angle between the output link and the direction of the reaction force of a gas spring. The ideal torque generated by a gas spring is 60 Nm throughout the movement angle of the output link. The error of the mean

TABLE 3.1: Required specifications of the proposed active rotary-legs mechanism

Gas spring	KPF50-50 weight 320 [g] reaction force 490-609 [N] length 0.246-0.196 [m]
Link length [m]	input | 0.04, intermediate | 0.19, output | 0.23, fixed | 0.27
Motor	maxon EC-motor 50 [W] planetary gear head GP42C (66:1) weight (with gear head) 720 [g] nominal volt 24 [V] nominal torque 0.131 [Nm] nominal speed 4500 [rpm]

square between the ideal torque and the torque generated by a gas spring is then calculated.

4. If all possible gas springs are investigated with respect to the current movable/fixed position, the investigation procedure returns to step 2) after changing the movable fixing position from the current position. The displacement is 0.01 [m]. If all gas springs are investigated with all movable position within the allowable area, the investigation procedure returns to step 2) after changing the fixing position from the current position. The movable position also returns to the initial position.

5. After finishing the all investigations, the gas spring and its movable/fixed positions with the smallest error of mean square between the ideal torque and the torque generated by the gas spring are selected for the proposed active rotary-legs mechanism.

The torque characteristics are described in Section 3.3.1. Moreover, the detailed structure of the active rotary-legs mechanism is described in Section 3.4.

3.3 Simulations

3.3.1 Simulation of active rotary-legs mechanism

The required specifications for the proposed active rotary-legs mechanism is investigated based on the strategies in the previous section using MATLAB. Figure 3.5 shows the simulation results of the proposed active rotary-legs mechanism. Table 3.1 lists the specifications of the active rotary-legs mechanism.

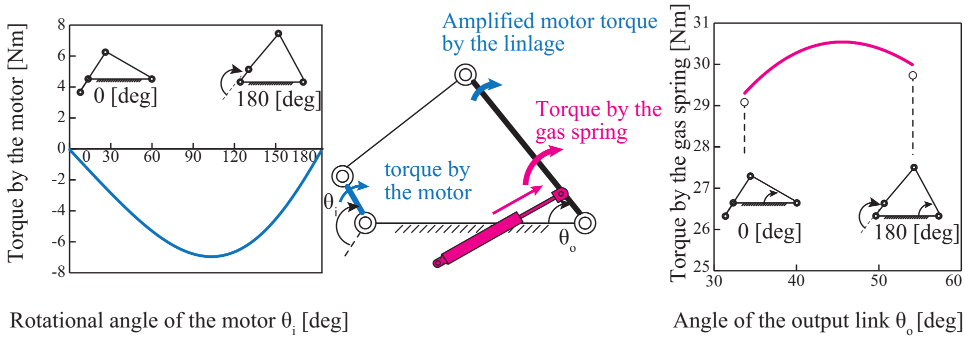


FIGURE 3.5: Simulation results for determining the optimal motor and the gas spring for proposed active rotary-legs mechanism. The left side shows the required input motor torque, while the right side shows the output torque generated by the selected gas spring.

Firstly, the simulation results suggest that using only one motor is not desirable, since the load force acting on the input link where the motor shaft is connected is calculated as more than 360 N, which can exceed the allowable load of the motor shaft. Thus, two motors are implemented so that the motors cannot breakdown. According to this strategy, one gas spring as well as one motor are used for one 4 bar linkage mechanism, which the whole mechanism has two motors and two gas springs in total.

The left side of Figure 3.5 shows that the maximum input torque required for one motor to ensure the maximum output torque over one cycle is less than 8 Nm. The angular displacement of the output link is approximately 20 deg over one motor cycle as shown in the right side of Figure 3.5. The mobility device can climb up one step after the rotary-legs rotate 120 deg. Therefore, the required motor should rotate at more than 60 rpm to satisfy the time requirement mentioned in Section 3.2. Moreover, the right side of Figure 3.5 shows that the output torque generated by one gas spring is approximately 30 Nm while the linkage is operating. Thus, the total torque generated by the gas springs is approximately 60 Nm.

Second, the results indicate that the required motors consume only 100 W in total for the stair-climbing. The total required energy consumption is less than that for planar locomotion of regular powered wheelchairs [100]. This would suggest that the proposed mechanism design that distributes torque requirements has potential to develop energy efficient stair-climbing mobility device. In addition, the overall weight of the mechanism is approximately 2.08 kg without the battery and the linkage. The size is also small enough to be installed into the previously developed stair-climbing mobility device.

TABLE 3.2: Specifications of the reduced scale prototype

Gas spring	FGSS15050B reaction force 98-127 [N] length 0.246-0.196 [m]
Link length [m]	input ∣ 0.04, intermediate ∣ 0.22, output ∣ 0.26, fixed ∣ 0.26
Motor	maxon DC-motor 20 [W] planetary gear head GP026A (4:1) nominal volt 18 [V] nominal torque 0.0229 [Nm] nominal speed 8850 [rpm]

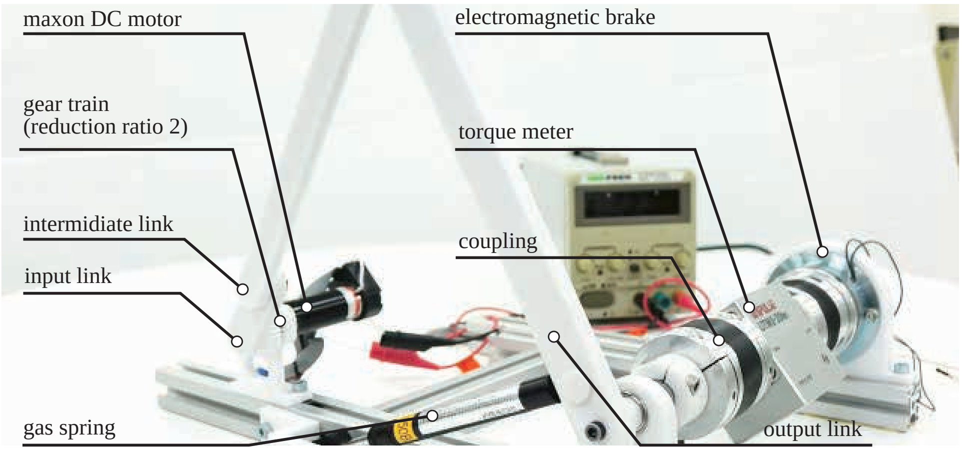


FIGURE 3.6: Overview of the developed reduced scale prototype.

3.3.2 Preliminary Experiment to Evaluate Reduced Scale Prototype

Before developing a stair-climbing mobility device with the proposed mechanism, a reduced scale prototype is developed based on the simulation results mentioned in Section 3.3.1. The reduced scale prototype is shown in Figure 3.6. This is because, whether the proposed mechanism can generate a maximum required torque over one motor cycle must be checked to verify the simulation adequacy. Next, whether the stair-climbing mobility device with the proposed mechanism can climb stairs by rotating the rotary-legs must be verified. This is the reason why the reduced scale prototype is developed before making the fully equipped stair-climbing mobility device.

Experimental Procedure

In the reduced scale prototype, an electromagnetic brake, whose static and dynamic friction torques are 5.5 Nm and 5 Nm, respectively, is

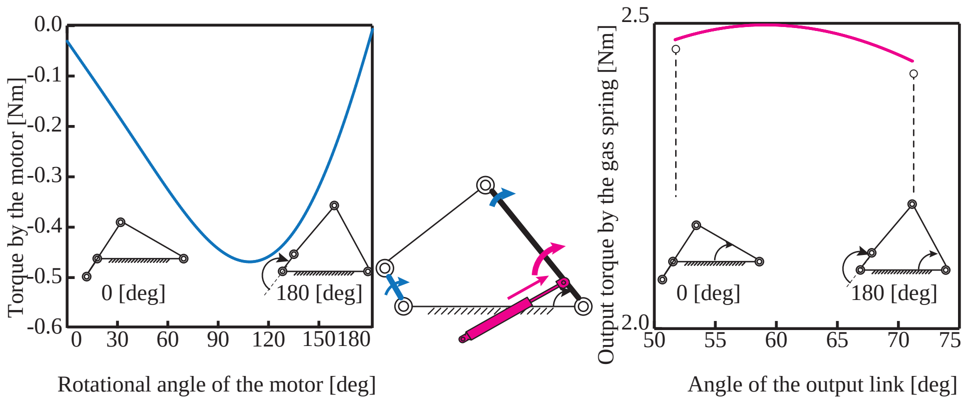


FIGURE 3.7: Simulation results for determining the optimal motor and gas spring of the reduced scale prototype. The left side shows the required input motor torque, while the right side shows the output torque generated by the selected gas spring.

connected to the shaft of the output link through a rotational torque meter UTMII (UNIPULSE Co., Ltd.). The torque meter measures the output torque by detecting the torsion of the output shaft. The electromagnetic brake is used to check whether the reduced scale prototype can generate the required torque over one motor cycle. The simulation validity can be confirmed if an appropriately designed reduced scale prototype could work against the brake. The purpose of this preliminary experiment is to operate the prototype against the friction torque by the brake, assuming that the friction torque as a maximum required torque for the stair-climbing. In the simulation, the desired torque by the motor and the gas spring are set to be 3 Nm and 2.5 Nm, respectively. Subsequently, required specification of the prototype is calculated using the same simulation. Figure 3.7 shows that simulation results to determine the suitable motor and gas spring for the prototype. Table 3.2 lists the specifications of the reduced scale prototype. A maxon DC motor was used at 9 VDC for the preliminary experiments. The motor shaft and the input link are connected with the gear train, whose reduction ratio is 2 to ensure the required input torque. According to the simulation results, the gas spring is connected to the output link, as shown in Figure 3.6. The shafts of the output link and the torque meter were coupled through a one-way clutch to transmit the friction torque in a single direction.

Results and Discussion

Figure 3.8 shows the experimental result of the reduced scale prototype. It is confirmed from the graph that the developed reduced scale prototype could generate the required maximum torque over one motor cycle and rotate against the friction torque generated by

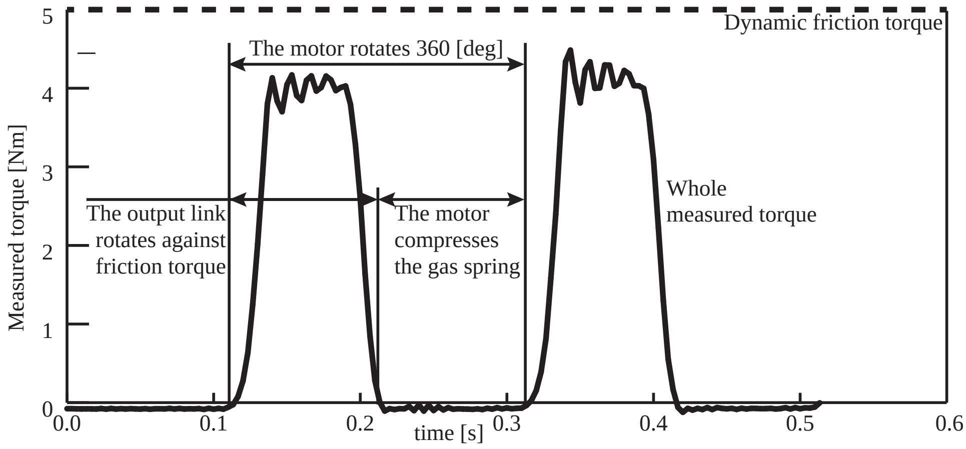


FIGURE 3.8: Experimental result of the measured torque of the reduced scale prototype.

the electromagnetic brake. However, the measured output torque was smaller than the friction torque. This is because, the torsion of the output shaft would not be accurately transmitted to the torque meter, which resulted in the experimental result.

The estimated maximum torque by the motor was calculated as approximately 0.66 mNm based on the entered current to the motor. The torque is larger than the set torque, since the motor should compensate for the transmission loss of the motor itself and the mechanical structure.

In conclusion, we suggest that the validity of the simulation is confirmed. Therefore, the combination of motors and gas springs with the 4 bar linkage mechanism has potential to generate the required torque over one motor cycle for the stair-climbing mobility device. We then work on developing fully equipped stair-climbing prototype.

3.4 Stair-Climbing Mobility Device with Active Rotary-Legs Mechanism

In the previous section, we confirmed the validity of the simulation. We then describe the fully equipped stair-climbing mobility device in this section.

Figure 3.9 shows an overview of the stair-climbing mobility device with the developed active rotary-legs mechanism. It consists of a pair of manual wheels (22 inch) which are used for a regular manual wheelchair, primary frames, and a pair of active rotary-legs mechanisms using 4 bar linkages, motors, and gas springs. The length of the linkage mechanism and the specification of the motor and the gas spring are selected according to the aforementioned simulations.

TABLE 3.3: Specification of the mobility device with the active rotary-legs mechanism

Dimension	Width 67 [cm] Length 78 [cm] Height 70 [cm] Wheelbase 32.5 [cm]
Weight	Overall weight 19 [kg] Weight of the developed actuator 4.8 [kg]

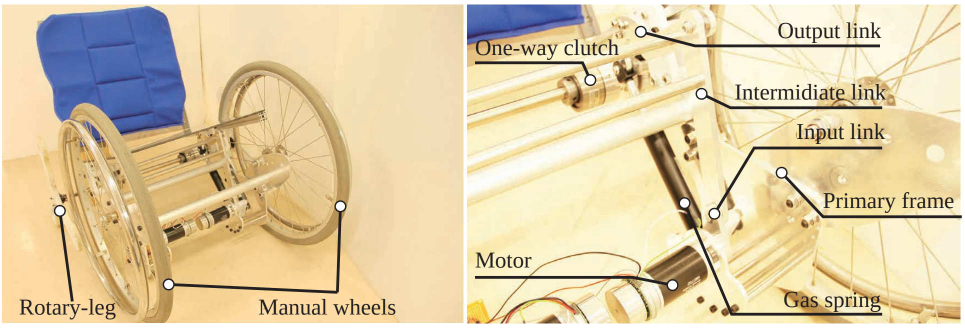


FIGURE 3.9: Overview of the developed prototype of the mobility device with the active rotary-legs mechanism.

Two 50 W maxon EC motors are installed for the mechanism to distribute the load against the motor shafts. Other stair-climbing mobility devices are equipped with more than 150 W motors for the actuators [56, 61]. On the other hand, the proposed mobility device consumes less power for the stair-climbing, which has an advantage in terms of energy efficiency. Table 3.3 lists the overall specifications of the mobility device.

The output link of the active rotary-legs mechanism and the rotational shaft of the rotary-legs is connected through the one-way clutches. Thus, we note that we need to reassemble the one-way clutches for climbing down the stairs which poses some inconvenience in the current prototype. The ratchet mechanisms are also installed to the rotational shaft so that the rotary-legs can keep the posture after every one motor cycle. Through these mechanisms, the rotary-legs rotate at a certain angle and maintains their position at each interval, which realizes the stair-climbing procedure. The seat angle is adjusted for the stair-climbing procedure based on a previous study [81]. The seat angle is inclined 25 deg backward with respect to the horizontal plane prior to the stair-climbing procedure.

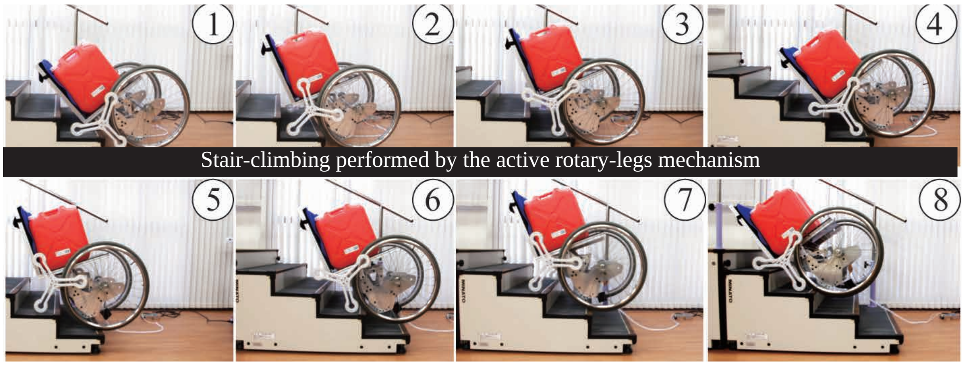


FIGURE 3.10: Experimental result of the stair-climbing by the active rotary-legs mechanism.

3.5 Performance Evaluation

I conducted stair-climbing experiments to verify the feasibility of the proposed active rotary-legs mechanism. The fundamental performance of the active rotary-legs mechanism is verified through the simulations and the preliminary experiment using the reduced scale prototype. The purpose of this experiment is to check whether the mobility device can climb up stairs by the proposed active rotary-legs mechanism.

3.5.1 Experimental Procedure

The stair-climbing experiment using indoor stair was conducted to verify the feasibility of the proposed active rotary-legs mechanism. In this experiment, the riser and the tread of the stairs were 125 mm and 300 mm, respectively. A 32.5 kg weight was used instead of a human participant for the first stair-climbing experiment to check the performance of the mechanism itself. This is because, it must be checked whether the mobility device can climb up, and whether any adverse event exists at the beginning. Testing the mobility device with human participants would be one of our future works. In this current design, the mobility device could climb up with a person of up to 80 kg, but also, 32.5 kg can be feasible because potential users also include children. Also, the simulation validity is already confirmed through the preliminary experiment using the reduced scale prototype. A stabilized power supply was used for the motor input so that the mechanism generates the required torque and rotational speed for the stair-climbing.

Results

Figure 3.10 shows the image sequence of the stair-climbing experiment. In the experiment, the developed mobility device with the

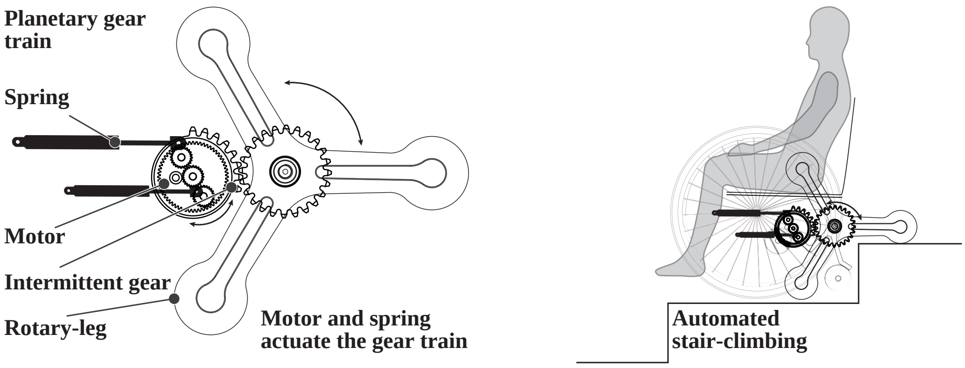


FIGURE 3.11: Concept of one of the possible future designs for the active rotary-legs mechanism.

active rotary-legs mechanism could climb up the stairs successfully without any accidents using the linkage mechanism with motors and gas springs.

However, it required approximately 33 s to climb up 3 steps, and the average required time was 11 s per step. Thus, the developed active rotary-legs mechanism could not satisfy the time requirement in this experiment. Also, the rotary-legs slipped after each motor cycle, when the manual wheels were about to climb up the step. The rotary-legs then slipped, while the manual wheels went down. This resulted in the requirement of additional time to climb up one step.

3.6 Design Guideline towards Future Active Rotary-Legs Mechanism

Design guideline towards future active rotary-legs mechanism is described based on the experimental results. The developed active rotary-legs mechanism rotates the rotary-legs at a certain angle per one motor cycle. This periodic motion would result in the slippage of the rotary-legs, which takes an additional time to complete the stair-climbing. Also, the mechanism is equipped with the one-way clutches, which does not support both climbing up and down the stairs. Therefore, we consider that a next active rotary-legs mechanism must satisfy the following conditions:

- An active rotary-legs mechanism must climb each step not intermittently, but continuously.
- A mechanism for switching the climbing direction is required to support both stair-climbing up and down.

Figure 3.11 shows one of the possible future designs of the active rotary-legs mechanism. The mechanism is designed based on the planetary gear train. In this mechanism, a sun gear is actuated

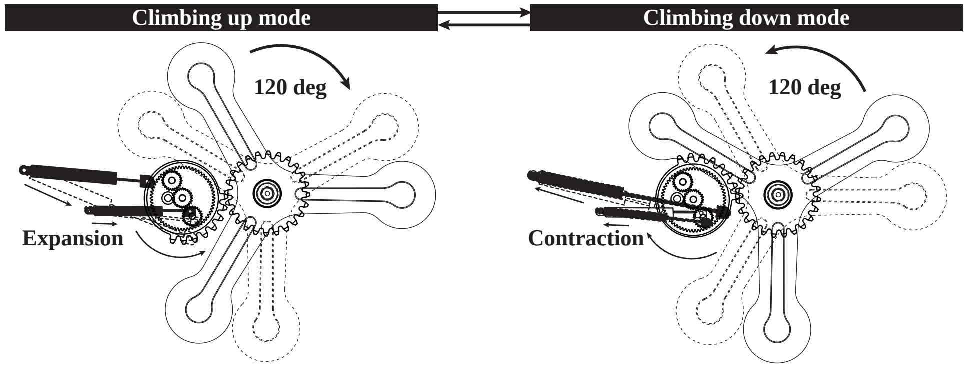


FIGURE 3.12: Working principle of the future design.

by a motor to rotate a ring gear while a carrier plate is fixed. The rotational motion of the ring gear is transmitted to the rotary-legs to climb up and down the stairs. The climbing direction can be changed by rotational direction of the motor. Furthermore, the mechanism has two different springs, where one spring is attached to the planetary gear, and the other spring is attached to the ring gear. In this manner, the design realizes the stair-climbing up and down continuously using the combination of the motors and springs with the planetary gear train.

3.6.1 Working Principle

Figure 3.12 shows the working principles of the future design of the active rotary-legs mechanism. This mechanism also has 2 phases similar to the developed version. The first phase is one where both the motor and the spring rotate the rotary-legs through the gear train. The second phase is one where the motor compresses the spring. Each phase works alternately when the spring takes its maximum/minimum length. The ring gear is equipped with an intermittent gear. The intermittent gear rotates at certain angles along the lines with the outer circumference of the ring gear. This design allows the intermittent gear to connect the rotary-legs in a different mode for both stair-climbing up and down. In the mode of climbing up the stairs, the intermittent gear is connected to the rotary-legs when the motor and the spring exert the torques in parallel. In the mode of climbing down the stairs, the intermittent gear is connected when the spring is compressed, which the spring could be utilized for damping to climb down the stairs safely.

3.6.2 Characteristics of Spring

Gas spring is also chosen for the future design for its compactness with sufficient output force. In general, generated torque by the spring which is attached to a rotational system describes a sine wave

TABLE 3.4: Required specification of the future design.

Gas spring	KPF120-70 (for ring gear) FGSS15050B (for planetary gear)
Planetary gear train(teeth number)	sun gear ∣ 25, planetary gear ∣ 25, ring gear ∣ 75
Motor	maxon EC-motor 50 [W] Planetary gear head GP42C (66:1) Using a gear whose teeth number is 12

by its expansion and contraction. In the developed mechanism, since the angular displacement of the output link is approximately 20 deg per one motor cycle, the generated torque by the spring satisfies the torque requirements for climbing stairs. However, the angular displacement in the future design is 120 deg. Therefore, there is a concern that the mechanism cannot exert enough torque during climbing each step.

To deal with the problem, Fourier series expansion of a square wave is utilized for the future design. The result of the expansion of the square wave is expressed as superposition of sine waves whose frequency is odd. Therefore, an appropriate gear train with springs whose the sum of generated torque corresponds to the Fourier series expansion has potential to generate enough torque during climbing each step. In the future design, the planetary gear train is selected to realize the required torque for stair-climbing. First and second term of the expansion are utilized to approximate the required torque for the stair-climbing as follows:

$$\tau_s \leq \frac{4\tau_{de}}{\pi}(\sin(\theta) + \frac{\sin(3\theta)}{3}) \tag{3.6}$$

where τ_s denotes the required torque for the stair-climbing, τ_{de} and ϕ denote the variables which a designer can modify to adjust the required torque in the working phase [$\phi \leq \theta \leq \phi + 120deg$].

3.6.3 Simulation

The same requirements for the developed active rotary-legs mechanism are set to design the future design as follows:

- The maximum required torque is approximately 130 Nm.
- The target time for climbing one step is 6 s.
- The stair-climbing design does not require any position and speed control for the rotary-legs.
- The proposed mechanism can also potentially allow a user to control the rotary-legs using the lever propelling action manually.

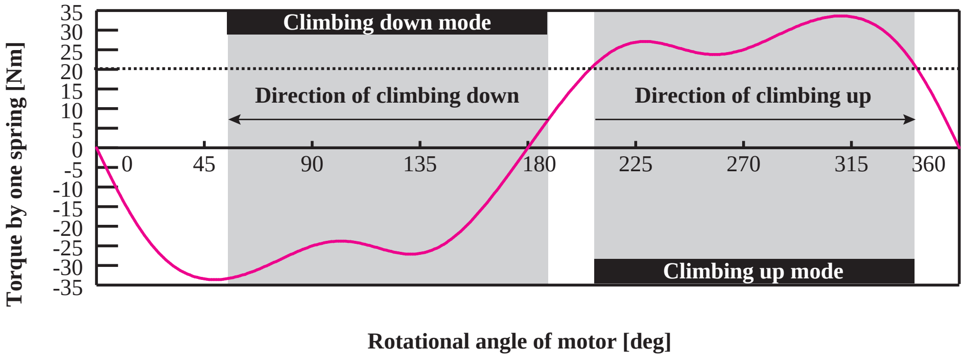


FIGURE 3.13: Simulation result regarding generated torque by the spring through the planetary gear train.

In the future design, considering hysteresis of the spring and the mechanical design, the torque generated by the motor, and the torque generated by the springs are set to be 90 [Nm] and 40 Nm, respectively. Also, the same algorithm is applied to select the suitable gas spring. We note that one gas spring as well as one motor are used for one planetary gear mechanism, which the whole mechanism has two motors and two gas springs in total.

Simulation Results

Figure 3.13 shows the simulation result regarding generated torque by the spring through the planetary gear train. Table 3.4 lists the specification of the future design. We note that only 100 W motor in total can still operate the stair-climbing up and down procedures. The torque generated by the spring has 2 phases. In the climbing up mode, the generated torque shown in the right side of Figure 3.13 can be utilized. On the other hand, in the climbing down mode, the generated torque shown in the left side of Figure 3.13 can be utilized as a damper. Switching of the mode can be realized by the intermittent gear which rotates at certain angles along the lines with the outer circumference of the ring gear. Furthermore, the required time for climbing one step can be calculated as 5.5 s, which satisfies the target time. Therefore, the proposed active rotary-legs mechanism using combination of motors and springs would have potential to realize more energy efficient stair-climbing mobility devices.

Chapter 4

Case study C: Standing Mobility Device with a Passive Step-Climbing Mechanism

4.1 Background

Through Chapter 2 and 3, we confirmed the following findings.

- A proper shifting of overall COM position within a desired range through user's posture transition would contribute to stair-climbing using only user's upper body strength.
- An overall COM position shifting would also contribute to more energy efficient stair-climbing mobility devices using a parallel elastic mechanism which distributes required torque requirements between active and passive components.

Therefore, we would suggest that one of the critical problems regarding locomotion using wheelchairs, i.e. stair-climbing, would be able to be solved by a proper COM position shifting and designing torque distribution. Therefore, wheelchair users would be able to extend their accessible areas in terms of locomotion.

However, when we pay attention on their posture, they are still forced to live with sitting posture. As we mentioned in Chapter 1, standing mobility devices are placed more expectations to deal with the problem. Thus, mobility devices for assisting posture transition between sitting and standing have been proposed so far [35–37]. Some of the standing mobility devices have already been commercialized in different countries [39–41].

Regarding their locomotion mechanisms, they are wheeled mechanisms equipped with small size of wheels, since they are supposed to be used not only outdoor, but also indoor where locomotion spaces are relatively narrow. It implies that the size of wheel would be restricted for the target environments. Also, the overall COM position tends to be higher because a user takes standing posture, which leads higher risk of falling accidents. This would lead a limited capability to overcome rough terrain including a single step. Thus, standing mobility devices must be improved regarding locomotion capability

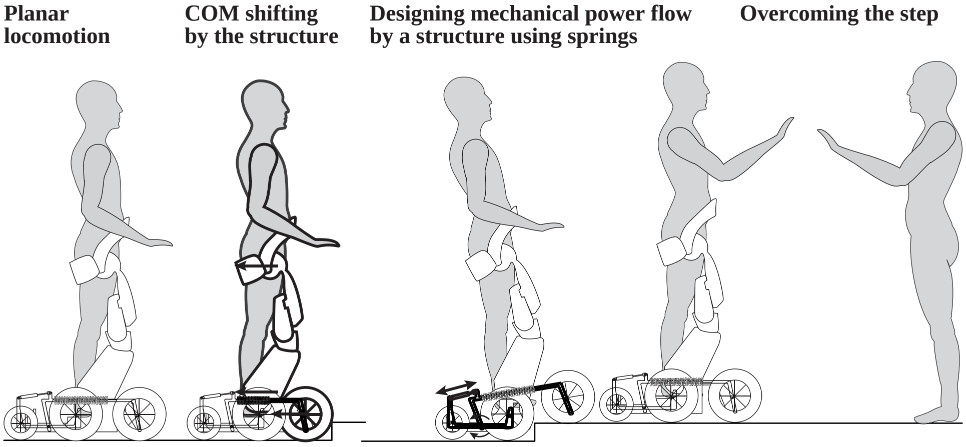


FIGURE 4.1: Concept of the case study C.

for more daily usage scenarios. Especially, I consider that overcoming a single step stably with standing mobility devices is a starting point for extending their locomotion functionalities.

4.2 Related Works

As we described in Chapter 1, research and development of step-climbing mechanisms for wheelchairs [47–50] and rovers [51–53] have been conducted thus far. Findings of the researches would also contribute to improve the locomotion capability of standing mobility devices. However, they would consider a user as a weight on a mobility device, which previously proposed mechanisms did not include human explicitly. Thus, the mechanisms leave an important room for considering step-climbing with human and machine.

4.3 Purpose

The purpose of the case study C is to propose a step-climbing methodology with human and machine for standing mobility devices. Figure 4.1 shows the concept of the proposed step-climbing methodology. The proposed methodology utilizes a proper COM position shifting through posture transition of a user. It also utilizes mechanical power flow, which the mechanism stores, divaricates, and releases energy at a desired timing. As we already described, we first focus on step-climbing with standing posture towards more challenging situations such as stair-climbing. We consider that not only realizing stair-climbing, but also performing step-climbing would be beneficial for users. In this case study, we describe fundamental step-climbing methodology and preliminary experiments to verify feasibility of the proposed design.

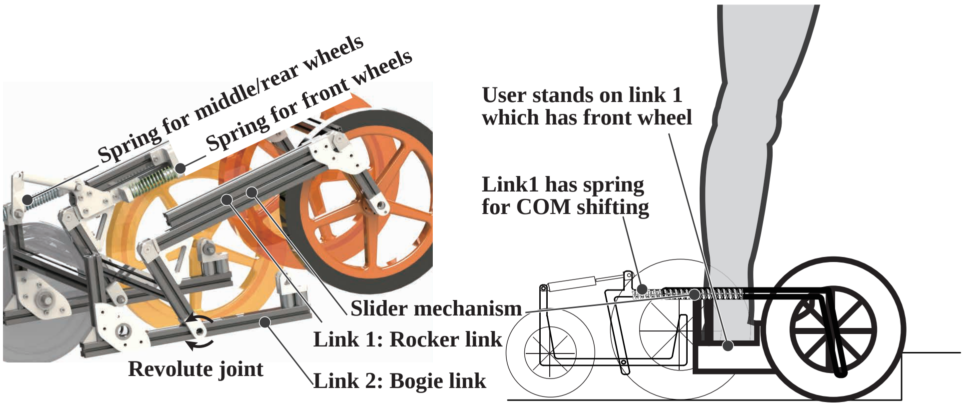


FIGURE 4.2: Schematic diagram of the proposed step-climbing methodology for standing mobility device.

4.3.1 Scope of Support Target and Step

In the case study C, we consider both manual and powered wheelchair users as main supporting target since the mobility device would be designed based on a standing mobility device. In addition, people who can stand and walk could also be considered as target users since standing mobility devices can be used not only people with lower limb impairment, but also people who can stand and walk in certain situations. Segway is one of the common examples [101].

Regarding target step height, we consider curbstones could be one of the biggest obstacles when using mobility devices such as regular wheelchairs. Curbstones restrict pathway when crossing a street using wheelchairs since overcoming curbstones requires certain skills such as wheelie motion. Not all wheelchair users can perform the wheelie motion stably to overcome. At least one helper is often required for user safety. Subsequently, we set the maximum step height to be 150 mm according to Japanese standards of a curbstone at the beginning of the proposed step-climbing methodology [102].

4.4 Design of Step-Climbing

An overview of the proposed step-climbing methodology for standing mobility device is shown in Figure 4.2. Firstly, we note that the proposed mobility device has an exoskeleton which can maintain user's standing posture regardless of their lower limb conditions. The mobility device enables planar locomotion and step-climbing by changing user ' s position on the mobility device, and by storing/releasing energy at a desired timing.

The proposed mobility device is designed based on a rocker-bogie mechanism to ensure safety during step-climbing. Thus, the mobility device has 6 wheels in total. It has a pair of front, middle, and rear

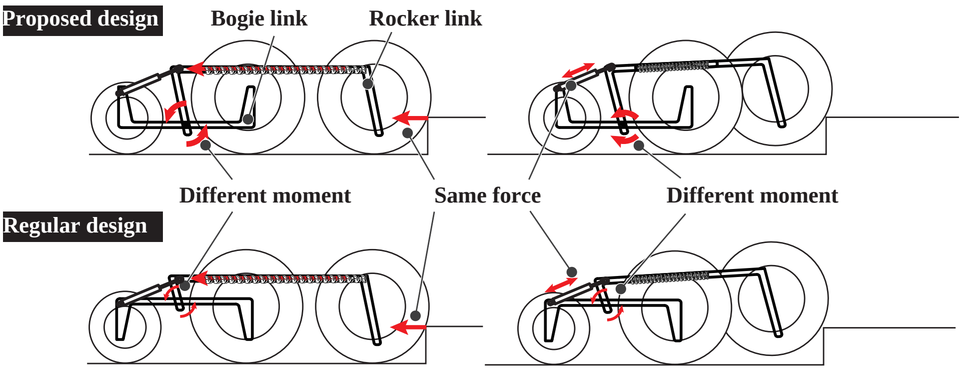


FIGURE 4.3: Fundamental concept of the proposed rocker-bogie based mobility device.

wheels. This structure has enough contact points to realize a proper shifting of the overall COM position for the step-climbing. The middle wheels are actuated by motors for planar locomotion, and other wheels are casters. The caster could be an omni-directional wheel to make the mobility device to be compact and to ensure ability to turn in a small radius for adapting narrow spaces. The rear wheels as well as middle wheels are actuated when climbing the step. The motor torque from the middle wheel is transmitted to the rear wheel using a transfer mechanism such as pulley and sprocket.

The mobility device has a slider mechanism for a proper shifting of overall COM position. The front and the user can be moved by the slider mechanism so that the mobility device climbs the step by the proper COM position shifting. The slider mechanism is equipped with springs so that the front wheels can maintain and return its neutral position when no forces are applied. In addition, the mobility device is equipped with another springs between the link 1 which has front wheels and the link 2 which has middle and rear wheels. This structure transmits the mechanical power properly so that the mobility device can climb the step stably.

4.4.1 Rocker-Bogie based Mechanism

In general, a rocker-bogie mechanism consists of 2 different type of links, which are called rocker and bogie link, respectively. The term rocker represents its rocking motion and it is connected to the bogie link by a revolute joint. The term bogie represents the link which have drive wheels attached at each end of the link. The bogie is usually used for mobility devices which are supposed to carry heavy loads. Generally, the mechanism has 6 wheels in total, and 3 wheels are attached to right and left side of the mechanism for front, middle, and rear wheel, respectively. By this configuration, a rocker-bogie mechanism has higher locomotion capabilities for rough terrain including a single step without restricting size of each wheel.

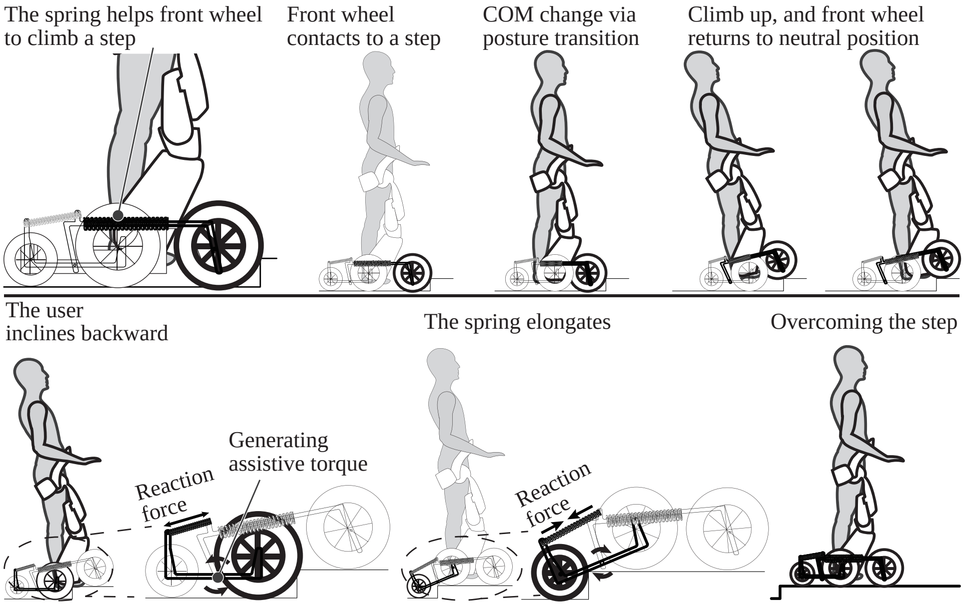


FIGURE 4.4: Working principle of the proposed step-climbing.

Figure 4.3 shows the fundamental concept of the proposed mobility device structure for step-climbing. First, the proposed mechanical structure is designed based on a regular rocker-bogie mechanism so that the all wheels can overcome the step stably. Especially, the proposed bogie link is designed based on a reverse design of a regular bogie link. The whole structure is designed so that the moment arm for climbing up is large enough for the step-climbing. Also as already described, the proposed rocker link has a slider mechanism to perform a proper movement for the front wheels and a user.

4.4.2 Working Principle

Standing mobility devices are mostly supposed to move around on flat surfaces, and the planar locomotion capability is one of the most essential capabilities for any assistive mobility devices. Thus, we consider that the proposed step-climbing mechanism must maintain the planar locomotion capabilities similar to a regular mobility device such as wheelchairs. This leads to a design guideline that the user's neutral position is close to the drive wheels. However, the user's position would be different from an ideal position for step-climbing. In addition, size of the wheel is restricted according to target environments. We consider that these could be primary reasons that mobility devices cannot climb even a single step stably just by rotating drive wheels by motors.

In this case study, we consider that shifting overall COM position to a desired range for step-climbing would also be effective. In addition, the step-climbing methodology is designed while focusing on storing and releasing energy for stable step-climbing. Figure 4.4 shows the image sequences of the proposed step-climbing methodology. Neutral position of the user is close to the middle wheels which are the drive wheel for planar locomotion. Next, before entering the step-climbing mode, the torque is transmitted to the rear wheels by a transfer mechanism such as pulley and sprocket.

First, the front wheels contact to the step by rotating the middle and rear wheels. The slider mechanism with the spring then compresses while the front wheels contact to the step, which reduces the normal force acting on the front wheels through COM position shifting. This makes the front wheels start to climb the step. In addition, the stored energy in the spring is utilized for front wheels to return its neutral position after climbing the step. After the front wheels finish to climb the step, the slider mechanism returns to its neutral position by the force stored in the spring. Second, the spring which is connected between link 1 (rocker link) and 2 (bogie link) plays a significant role for middle and rear wheels to climb up the step. The spring compresses while the front wheels climb up the step since the link 1 with a user inclines backward, which generate counterclockwise torque to the link 2. This reduces the normal force acting on the middle wheels while increasing the normal force acting on the rear wheels, which the middle wheels can climb the step. Last, the spring elongates while the middle wheels climb up the step, which generates clockwise torque to the link 2. This increases the normal force acting on the middle wheels while reducing the normal force acting on the rear wheels, which rear wheels can climb the step.

As we just described, energy can be stored, and released at desired timing, and divaricated to right direction for step-climbing by designing the mechanical structure based on a regular rocker-bogie mechanism. By designing the overall COM position and the mechanical power flow, the step-climbing with standing posture can be realized stably.

4.5 Preliminary Evaluations by Simulation

Before introducing a fully equipped step-climbing mobility device, we conducted preliminary evaluations of the proposed step-climbing mobility device by using simulations. The purpose of the preliminary evaluations is to check feasibility of the proposed step-climbing mobility device, and to find out a suitable mechanical parameters for introducing a prototype.

TABLE 4.1: Conditions for preliminary step-climbing simulations.

User's total weight 50/80 [kg]	shank 4.65/7.44 kg thigh 10/16 kg upper body 33.9/54.24 kg
User's total height 1.5/1.8 [m]	shank 0.369/0.4428 m thigh 0.3675/0.441 m upper body 0.705/0.846 m
User's leg position	8 mm backward from center of middle wheel 128 mm from the ground
Mobility device	size of front/middle wheel 16 [inch] size of rear wheel 12 [inch] weight acting on front/middle wheel 120 [N] weight acting on rear wheel 60 [N]

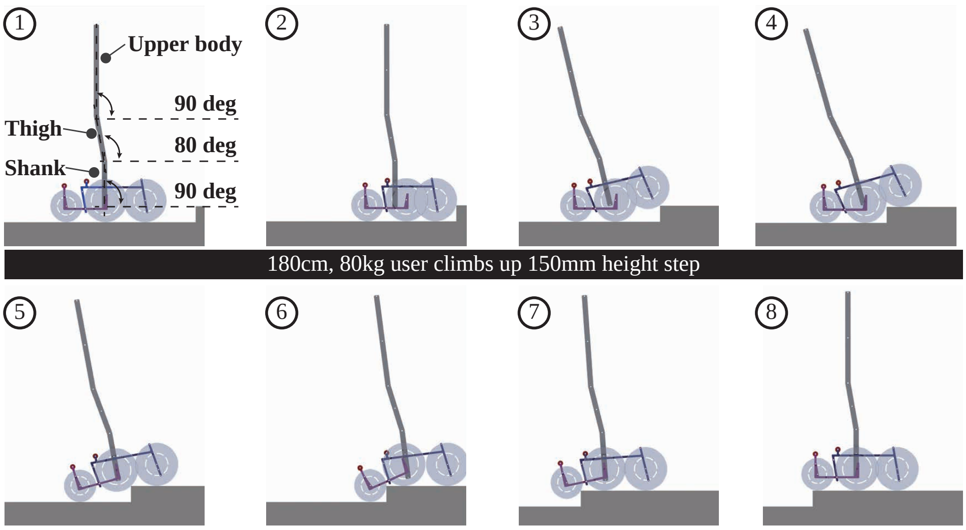


FIGURE 4.5: Simulation results of the proposed step-climbing methodology.

4.5.1 Evaluation Procedures

We used Solidworks Motion Analysis for the simulations, since it has enough accuracy to check the feasibility of the proposed step-climbing design, and is easy for designers to modify the mechanical structures based on simulations results. In this simulations, the target step height is set to be 150 mm. In addition, we used a three degree-of-freedom (DOF) planar link model by considering the shank, thigh, and upper body to simplify the simulations. The user's posture is fixed during step-climbing simulations, which we exclude influence of motion of a user on a mobility device for the preliminary evaluations. Table 4.1 lists the simulation conditions. In this simulations, we used 2 different user's physical parameters. One is that the user is 50 kg, and 150 cm, while the other is that the user is 80 kg, and 180 cm, respectively. We chose the different height and weight parameters since the user takes standing posture, which the overall

COM position is highly affected by the user's height. This would affect not only step-climbing capability, but also influence stability of the whole mobility device. Therefore, we performed simulations with the parameters to check the feasibility.

4.5.2 Results

Figure 4.5 shows the image sequences of one of the simulation results of the step-climbing. First, we confirmed that the proposed step-climbing mobility device with the different user's physical parameters could climb up the target step without falling accidents. In the initial phase of the step-climbing, the slider mechanism with springs changed the position of front wheels and the user so that the front wheels start to climb the step. After the front wheels climbed the step, it returned to its neutral position by the springs. However, it is worthy to note that springs with inadequate reaction force did not return the wheels to its neutral position, which resulted in falling down accidents. In addition, it is noted that certain amount of displacement is required for the front wheels to climb up. Further, spring with too strong reaction force cannot be compressed by the motor torques, which the mobility device cannot start to climb the step.

Second, the middle wheels could climb the step owing to the spring between the rocker and the bogie links. It is also worthy to note that the inadequate reaction force by the spring resulted in falling down accidents. The spring could maintain the user ' s posture not to fall down during step-climbing, and to generate the counterclockwise torque for middle wheels to climb the step at the same time.

Third, the rear wheels could also climb the step by the elongation of the spring, which generates clockwise torque for the rear wheels to climb the step. It is noted that the inadequate spring with too strong reaction force resulted in falling down accidents, since the spring also pulls the rocker link while generating the assistive torque for the rear wheels. On the other hand, spring with too weak reaction force cannot make the rear wheels to climb the step because of inadequate assistive torque.

In conclusion, the proposed step-climbing mobility device has potential to climb the target step regardless of user's physical parameters while taking standing posture. By not only the overall COM position shifting, but also designing the power flow in the mobility device, the step-climbing would be realized. Although an optimization process should be needed, we suggest that key design parameters of the proposed step-climbing mobility device are as follows.

- User's standing position on the mobility device, and displacement of the slider mechanism.

TABLE 4.2: Configuration of the developed prototype of the step-climbing mobility device.

Dimension [cm]	Width 70 Length 105 Height 115
Total weight [kg]	30.5
Springs	k = 1.03 (for the slider mechanism) k = 5.23 (between rocker/bogie links, for compression) k = 1.67 (between rocker/bogie links, for elongation)

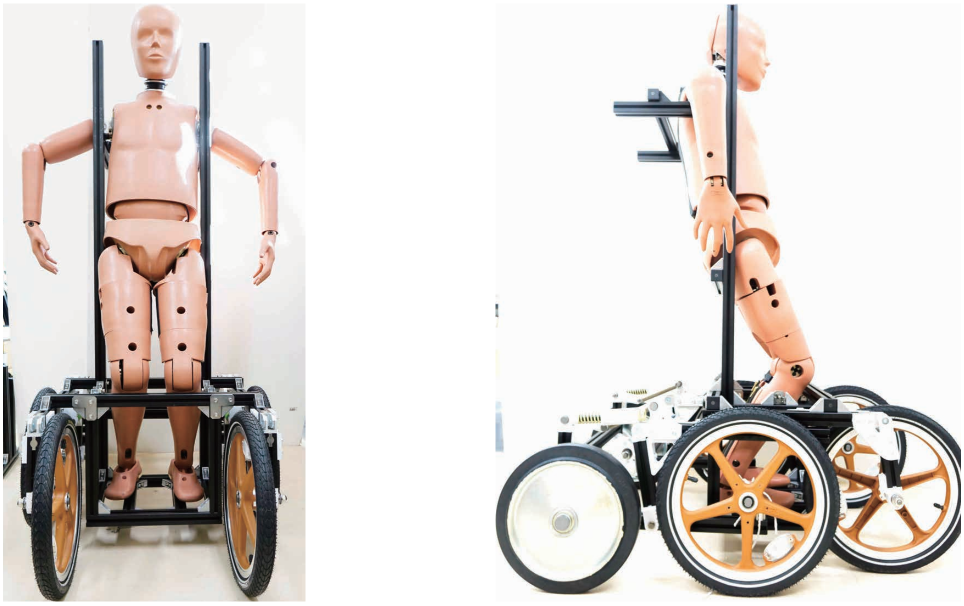


FIGURE 4.6: Overview of the developed prototype for step-climbing mobility device.

- Characteristics of the equipped springs, in terms of constant of the spring and attachment position.

4.6 Device Implementation

We developed a prototype of the step-climbing mobility device based on the aforementioned simulation results to check the feasibility in the actual environment. Figure 4.6 shows an overview of the prototype for the step-climbing mobility device with a dummy. Table 4.2 lists the specification of the prototype. The dummy is fixed to the primary frames, which the dummy maintains standing posture. It consists of a pair of front, middle, rear wheels, and primary frames based on a regular rocker-bogie mechanism. Each length of the primary frames and specification of each spring are determined according to the simulation results mentioned in Section 4.5. We chose the springs so that they have enough characteristics for shifting overall COM position and realizing enough mechanical power flow in the mobility device for the step-climbing.

For rapid prototyping and testing, we used plastic components whose shape is designed to connect 2 aluminum frames as a slider mechanism. Although the accuracy is not high enough for full production versions, we consider the component is suitable for the rapid prototyping and testing. Since the friction generated between the plastic component and the aluminum frame is relatively low, the slider mechanism would work smoothly under certain load conditions.

In the developed prototype, the diameter of front/middle wheel is 385 mm, which is smaller than 16 inch wheel that is used in the simulations. In addition, the diameter of rear wheel is 300 mm, which is also smaller than 12 inch wheel that is used in the simulations. Although the size of each wheel is not as same size as one used for the simulations, we consider that the feasibility could be checked by modifying the experimental conditions appropriately. Furthermore, no motor is equipped into the developed prototype, since the purpose of introducing the prototype is to check feasibility of the step-climbing methodology.

We install the 3 different type of springs into the developed prototype on both right and left side. One is a regular compression spring, which is installed into the slider mechanism. In addition, the other 2 type of springs are installed between the rocker and bogie links. One is a regular compression spring, and the other is a tension spring whose constant of spring is different. Characteristics of each spring is determined according to the simulation results. We note that, in the simulation, constant of spring which is installed between the rocker and bogie links has same value. However, we found that the same constant of spring would not always ensure the stable step-climbing procedure form the simulations. This implies that an optimal constant of spring would be different between contraction and expansion of the spring. Therefore, we installed the different springs so we can easily modify the prototype and check the effectiveness, especially for future investigations.

4.7 Performance Evaluations

We preformed preliminary experiments to verify the feasibility of the proposed step-climbing mobility device. The purpose of the experiments is to check whether the proposed step-climbing mobility device could perform step-climbing stably, and to verify whether the mobility device could climb the target step by just rotating the middle/rear wheels.

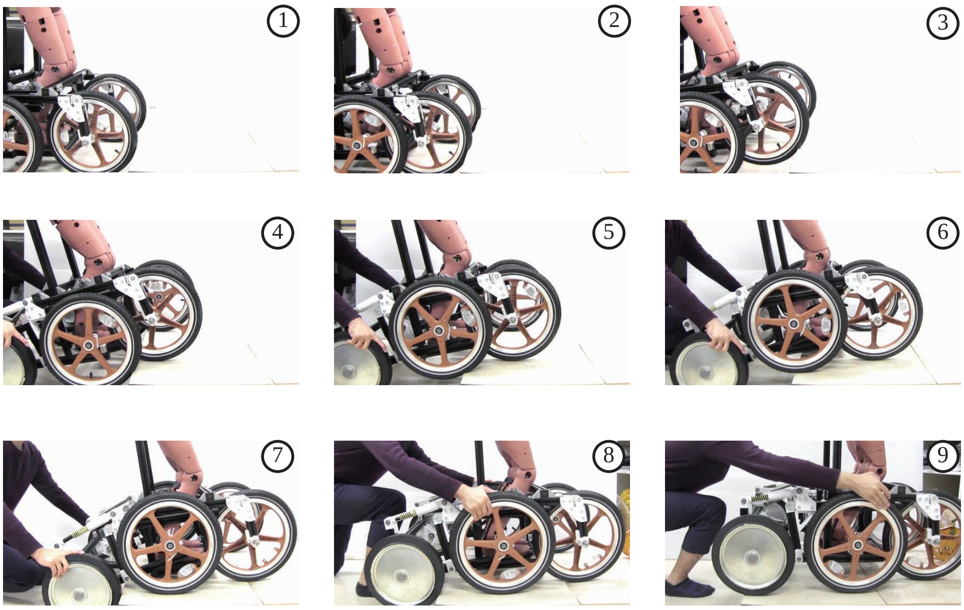


FIGURE 4.7: Experimental results of the step-climbing using the prototype.

4.7.1 Experiment for Step-Climbing

Experimental Procedures

First, experiment for step-climbing is conducted to verify the feasibility of the proposed step-climbing methodology using the developed prototype. We used a dummy (Hybrid-III5th Percentile Female Dummy, JASTI Co., LTD.) whose weight is modified to 60 kg for the preliminary step-climbing experiment. The dummy is tied to the frames of the mobility device so the dummy maintains standing posture. In the experiment, the step height is adjusted to 145 mm, since the size of the wheel of the prototype is smaller than that of simulations. The step height in this experiment is determined so that the same amount of driving force is required to climb the target step regardless of the wheel size. Also, instead of installing motors as an actuator, a person manually rotates the middle or the rear wheels so that the prototype can climb the step in this preliminary experiment.

Results

Figure 4.7 shows the image sequences of the step-climbing experiment. We confirmed that the developed prototype could climb the target step by shifting the overall COM position, and by designing proper mechanical power flow in the mobility device using the rocker-bogie based structures. In the initial phase of the step-climbing, the slider mechanism with the spring changed the position of front wheels and the dummy by rotating the rear wheels, which the prototype could start to climb the step. However, the slider mechanism

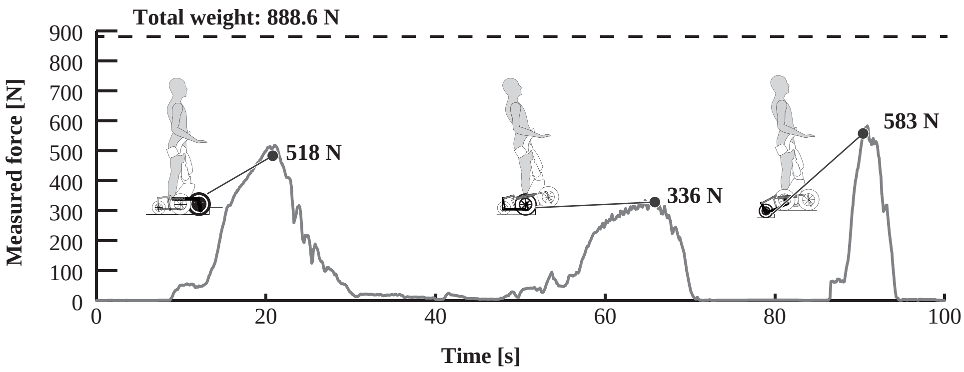


FIGURE 4.8: Experimental results regarding measuring required driving force.

did not return the front wheels to its neutral position smoothly after climbing the step. We note that the dummy inclined backward after the front wheels climbed the step, and maintained the posture by the spring installed between the rocker and the bogie links. We also note that the middle wheels slightly came off the floor by the spring force. The middle wheels then could climb up the step by rotating the rear wheels. Last, the rear wheels could also climb the step by rotating the middle wheels manually.

4.7.2 Experiment for Measuring Required Driving Force

Experimental Procedures

We then measured the required driving force for the prototype during the step-climbing to check whether the mobility device could climb the target step without slippage events. In the proposed step-climbing methodology, friction forces generated at the contact points between the drive wheels and the floor is the driving force for the step-climbing. Thus, we should check whether the mobility device could climb the step without slippage by comparing the driving force to the normal force acting on the wheels. In this experiments, the same dummy was used to measure the required driving force. In addition, the same height step was used for the experiment. The required force was measured by pulling a string which is attached to an axis of the middle wheels using a digital force gauge (ZP-1000, IMADA, CO., LTD.) horizontally. The same person pulled the string using the digital force gauge.

Results

The measured force for climbing the step is shown in Figure 4.8. The result shows that the measured driving force reaches local maximum when each wheel start to climb the step. The measured force then decreased as the wheel rotates. It is worthy to note that the measured force is less than the total weight of the prototype with the dummy. However, we note that the normal force acting on each wheel was not verified during the step-climbing. Especially, normal force acting on the front wheel is important since negative value of the normal force corresponds to the fact that the mobility device would in a progress of falling down.

Chapter 5

Discussion

We have conducted series of experiments to verify the feasibility of the proposed step/stair-climbing mobility devices. In this Chapter, we discuss respective experiments and the proposed step/stair-climbing mobility devices, with justifications and limitations. Some of the simulations and experiments to prove simulation results are not discussed here, since the objective is simply basic testing of the proposed methodology performed in the development stage.

5.1 Case Study A

5.1.1 Planar Locomotion

Experiments regarding the planar locomotion showed that the proposed mobility device which is designed based on a regular manual wheelchair has locomotion capability similar to a regular manual wheelchair. The typical locomotion mechanism using the manual wheels and the casters would realize the performance. Thus, we suggest that a wheeled mechanism using manual wheels and casters would be beneficial for planar locomotion for stair-climbing mobility devices operated by a user.

limitations: We tested the mobility device indoors and outdoors. However, the test environments were almost flat surfaces. Thus, it is necessary to test in more severe conditions such as rough terrain towards daily usage for wheelchair users.

5.1.2 Posture Transition

Experiments regarding the posture transition showed that the proposed posture transition of a user was realized by user's upper body control. The posture transition based on the moment change by the user himself would be sufficient to realize the proper transition with the simple mechanism. This would suggest that wheelchair users could change their posture for both planar locomotion and stair-climbing by user themselves with a simple passive mechanism.

limitations: The experiment was performed by only the healthy participant who had controllable upper body. Therefore, it is required to conduct the posture transition experiments with people with SCI to observe whether the people can perform the posture transition, and to measure muscle activities how much upper body capabilities are required for the posture transition.

5.1.3 Stair-Climbing by Health Participants

Climbing Up Stairs

First, the stair-climbing experiment outdoor showed that the participant could perform the planar locomotion, posture transition, and climbing up the stair in sequence by the user himself. The experiment revealed that the proposed stair-climbing mobility device using the overall COM position shifting by the posture transition and the lever propelled rotary-legs has stair-climbing capability performed by user himself. However, we note that the rotary-legs slightly slipped when the manual wheels start to climb up each step. Insufficient friction coefficient between the rotary-legs and the stair surface would result in the slippage. The developed stair-climbing mobility device could climb up each step after the user also slightly bent his upper body backward, which would make enough friction force through the overall COM position shifting.

Next, the stair-climbing experiments indoor whose step height was higher than the step outdoor revealed that the proper COM position shifting by the user's posture transition would contribute to the stair-climbing by user himself. The insufficient overall COM position shifting by the user's posture transition could not realize the stair-climbing with the lever propelled rotary-legs. We suggest the proper user's posture transition on the mobility device would change the whole behaviour with the same input to the mobility device, which made the mobility device climb up the stair successfully.

limitations: The step height of the stair-climbing experiments was lower than the target step hight (200mm). Also, in the stair-climbing experiment indoor, the mobility device was not equipped with the proposed posture transition mechanism using the gas springs to observe whether the overall COM position shifting by a proper user's transition realized the stair-climbing.

Climbing Down Stairs

Experiment regarding climbing down the stair revealed that the participant could perform the stair-climbing down without any falling accidents. The energy dissipation based mechanism using the torque dampers would sufficiently realize the climbing down motion. In the process of the climbing down the stair, the mobility device has certain potential energy. The proposed methodology is designed based on a strategy how the mechanism utilizes the energy. In the developed stair-climbing mobility device, the user rotated the rotary-legs at certain angle, and the mobility device then started to climb down by its gravitational force. The proposed damper based mechanism dissipated the potential energy enough for the climbing down process. It could be indicated that the dissipated energy would be beneficial for the rotation of the rotary-legs at the beginning of the climbing down motion for easier operation by storing the energy instead of just dissipation. Therefore, it is indicated that focusing on, and designing the mechanical power flow during the stair-climbing up and down could be a key for stair-climbing with human and machine.

limitations: We tested the mobility device with limited stair dimensions by the healthy participant. It is necessary to conduct further experiments regarding climbing down stairs with more participants including people with SCI to check not only the mechanism performance itself, but also feeling during the process, since the climbing down process might make users to feel scary as if they are falling down.

5.1.4 Lever Propelled Direction

Experiment regarding measuring muscle activities with the different lever propelled direction showed that the different muscles were primarily activated for the motion during climbing up the stair. The experiment revealed that the muscles on shoulder and upper limbs were mainly used for the lever propelled operation regardless of the direction. However, it might be indicated that more shoulder and back muscles would be required for pulling the lever motion from the obtained EMG data of trapezius and erector spinae T10. It could be considered that the muscles would compensate for the reaction force from the levers which would make the user's upper body bend forward during the pulling motion. On the other hand, it could be considered that abdominal muscle would compensate for the reaction force which make the user's upper body bend backward when pushing the lever, which would result in more abdominal muscle activities. However, it seems there is no significant difference between the lever propelled direction. It could be considered that the backrest could compensate for the reaction force instead of activating the appropriate muscles. Therefore, the result indicates that the pushing motion would be appropriate for people with SCI during stair-climbing using the regular wheelchair based mobility device.

limitations: The experiment was conducted with one healthy participant. It is necessary to conduct further experiments with more participants to evaluate the effectiveness of the lever propelled directions.

5.1.5 End Users Test

Experiments regarding stair-climbing up with 3 persons with SCI vertebrae T11, T9, and T4, respectively, revealed that the proposed stair-climbing methodology using the overall COM position shifting though the user's posture transition and the lever propelled rotary-legs could be feasible. First, it was confirmed that the overall COM position shifting through the posture transition would contribute to the stair-climbing. In addition, pushing the lever operation could also contribute to the stair-climbing up by user themselves. It is worthy to note that the person with SCI vertebrae T4 could operate the lever propelled mechanism by user independently. The backrest would compensate for the reaction force by the lever so that the users with SCI could perform the stair-climbing up. Further, the participants reported that the lever propelled operation was not hard to perform. This report indicates that the lever propelled force would be reasonable for the target users who use manual wheelchairs for daily life. We note that all participants used secondly developed prototype which is equipped with the gear train whose reduction ratio is 1.7. Thus, a mechanism to adjust required force such as a gear train would be necessary based on upper body strength for extending support target.

limitations: The experiment was conducted without the posture transition mechanism using the springs to check feasibility of the proposed overall COM position shifting through the user's posture transition and the lever propelled rotary-legs. The experiments were started, assuming users already performed the posture transition through the mechanism. It is also necessary to conduct stair-climbing down experiments to check the whole performance of the proposed methodology.

5.2 Case Study B

5.2.1 Active Rotary-Legs Mechanism

Experiment regarding the stair-climbing with the developed active rotary-legs mechanism revealed that the proposed methodology that distributes torque requirements between active and passive components would contribute to energy efficient stair-climbing mobility devices. The output torque of the equipped motor for the developed prototype has a limitation. The motor itself cannot operate the rotary-legs since the motor cannot exert whole required torque. However, energy produced by the motor can be stored by the equipped springs temporarily. The motor with the stored potential energy in the springs can then operate the rotary-legs together. The important point is that designing mechanical power flow by storing temporarily, and releasing energy at a desired timing would contribute to the energy efficient stair-climbing mobility device. Furthermore, the output link of the developed active rotary-legs mechanism can be used for the original lever propelled operation. Therefore, users who do not possess enough upper body strength to operate the original lever propelled mechanism would be able to operate the mechanism with help of the active rotary-legs mechanism.

The rotary-legs slipped during the stair-climbing, especially when the manual wheels start to climb up each step. It is assumed that one of the primary reasons is insufficient friction coefficient between the rotary-legs and the step surface. Further experiments using a rubber with a relatively high friction coefficient must be conducted. This might contribute in reducing the required time for climbing one step, which can satisfy the target time requirement for stair-climbing. Also, we need to check the performance of the proposed mechanism which rotates the rotary-legs 120 deg per one motor cycle whether the mobility device could climb stairs without slippage.

limitations: The experiment was performed using a dummy instead of human participants for preliminary evaluations. It is necessary to conduct further experiments with human participants to check not only the performance of the proposed mechanism, but also how users feel the whole movement of the mobility device during the stair-climbing. Further, we need to perform experiments regarding climbing down stairs.

5.3 Case Study C

5.3.1 Step-Climbing Mobility Device

First, the step-climbing experiment revealed that the proposed methodology has potential to perform the step-climbing with the proper overall COM position shifting and the appropriate design of mechanical power flow. It is considered that the proper COM position would allow the mobility device to climb the step stably. The slider mechanism using springs is one of the required elements for changing the COM position within the desired range. However, we note that the slider mechanism did not work as smoothly as the simulations. It is considered that the prototype was equipped with the plastic components for the slider mechanism, which would not have enough accuracy for the slider mechanism. Inaccuracy and the relatively high friction coefficient resulted in the non-smooth movement. The rocker-bogie based mechanism combined with the springs would also contribute to the stable step-climbing. It is observed that the equipped spring supported the rocker link where the dummy was placed so that the dummy did not fall down during step-climbing. In addition, it is considered that the spring transmitted mechanical power from the rocker link to the bogie link, which generate assistive torque for the middle and rear wheels to climb the step.

limitations: In this experiment, the person manually rotated the middle and rear wheels. There might be a concern that the person involuntarily applied additional assistive force to the prototype so that it could climb the step. Thus, we note that the experimental results with a prototype equipped with motors to rotate the wheels would be different from the current results. Also, it is necessary to conduct further experiments using dummy with different height and weight to verify the feasibility of the step-climbing methodology. Further, it is necessary to consider user's upper body motion during step-climbing, since the movement would affect step-climbing performance and stability.

5.3.2 Required Driving Force for Step-Climbing

Experiment regarding measuring the required driving force during step-climbing revealed potential to realize step-climbing without slippage using the proper overall COM position shifting and the appropriate design of mechanical power flow. It is observed that the COM position control would contribute to the stable step-climbing. We tested the performance of the proposed methodology with only specific parameters. Therefore, it is assumed that an optimization process would lead better mechanical structure in terms of stability and energy efficiency.

limitations: In this experiment, the specific parameters with one dummy was used. As we mentioned, optimization process must be conducted to clarify the performance of the proposed methodology with limitations.

5.4 Step/Stair-Climbing with Human and Machine

We discuss step/stair-climbing with human and machine with all conducted experiments and the discussions. First, we summarize important findings from each case study as follows:

Case study A: A proper overall COM position shifting within the desired range would contribute to stair-climbing operated by user him/herself through the lever propelled mechanism. The proper COM position change can be performed through the user's posture transition on the mobility device.

Case study B: A proper design for mechanical power flow with the COM position shifting through the posture transition would

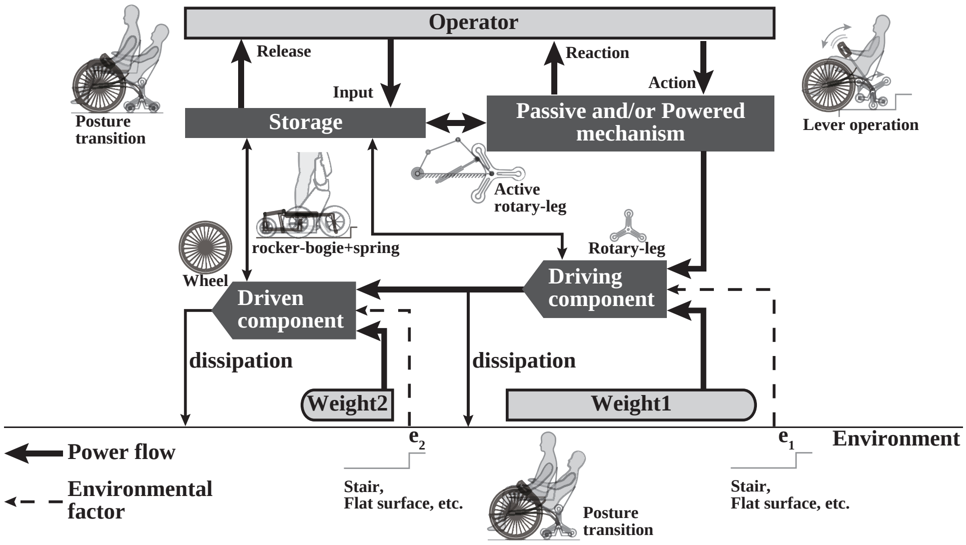


FIGURE 5.1: Concept of step/stair-climbing with human and machine. Required components and practical examples are shown. All of components are not always necessary, but must be selected based on requirements.

contribute to not only energy efficient stair-climbing mobility devices, but also realizing stair-climbing by users themselves through lever propelled mechanism with springs. A mechanism that stores energy temporarily, and releases the energy at a desired timing would be a key element for the stair-climbing.

Case study C: A proper overall COM position shifting would be performed passively by designing mechanical power flow in the mobility device. A mechanism that can change the COM position, and transmit mechanical power appropriately would be essential to overcome a single step.

Based on the obtained findings, we suggest that step/stair-climbing with human and machine is as follows:

Figure 5.1 shows a concept of the proposed step/stair-climbing with human and machine. First, it is necessary to consider an overall COM position with human and machine, since not only stability, but also behaviour of whole system is depending on the position. In other words, intensity of mechanical power flow among mechanical components and environment can also change by an overall COM position. Considering design of driving/driven components is another key design factor, since the design changes the required input power to operate. Next, a strategy to utilize human capability should be carefully designed based on their conditions and capabilities. Passive mechanisms such as lever propelled operation would be suitable if a user has enough strength to operate. One practical example is the case study A.

Powered mechanisms would also be required according to target users, especially according to their physical conditions. Subsequently, a mechanism to store mechanical energy would also be necessary to compensate for lacking energy to operate. Energy can be stored from human, a powered mechanism, or even kinetic energy from a whole system. One practical example is the case study B.

Last, divaricating the energy using mechanical structures would play an important role. A designer can control the power flow by designing connection among each mechanical components, which would realize step/stair-climbing. One example is the case study C. The step-climbing mobility device stores energy coming from motors and human movement, and utilizes it for step-climbing by the rocker-bogie based mechanism using springs.

In conclusion, step/stair-climbing with human and machine is, an overall COM position control through user's posture transition, and designing mechanical power flow by mechanisms and mechanical structure which can store, divaricate, and release mechanical power. This is my answer to the research question at present.

Chapter 6

Conclusions and Future Directions

In this research, we explored the research question of step/stair-climbing with human and machine. Based on the fundamental concept of mechanical power flow between human and machine, we conducted 3 case studies to find an answer.

First, we proposed a stair-climbing mobility device with lever propelled rotary-legs using human upper body strength in case study A. We described a series of theory to realize the stair-climbing by user him/herself. We then developed prototypes based on a regular manual wheelchair.

We verified feasibility of the proposed methodology through the experiments with healthy persons, a dummy, and people with SCI who use a manual wheelchair for their locomotion supporting device. The experimental results demonstrated feasibility of the proposed method to perform stair-climbing independently using posture transition of a user, and user's upper body strength. The stair-climbing experiments with the end users revealed that the stair-climbing could be realized by only user's upper body strength with a regular wheelchair based mobility device.

Second, we proposed an active rotary-legs mechanism for stair-climbing mobility device in case study B. The mechanism is designed based on the torque distribution between active components and passive components for more energy efficient stair-climbing mobility device. We described a series of design guidelines, conducted simulations, and preliminary experiments with the reduced scale prototype to verify the validity of the simulations. We then developed a prototype based on the previously developed stair-climbing mobility device which has a posture transition mechanism.

We verified the proposed methodology through the stair-climbing experiment with a dummy instead of human participants for safety consideration. The experimental results are preliminary, but demonstrated feasibility of the proposed method for energy efficient stair-climbing. Compared to other stair-climbing mobility devices, the developed prototype has only 100 W motors in total for stair-climbing.

Third, we proposed a step-climbing methodology for standing mobility device. The methodology is designed based on a regular rocker-bogie mechanism with an overall COM position shifting. We described a fundamental concept to realize step-climbing with a proper COM position shifting, and utilization of mechanical power flow. Also, preliminary simulations were conducted to observe feasibility of the proposed method. We then developed a prototype without active components to check the step-climbing performance itself.

We verified the proposed methodology through the preliminary experiments using a dummy with help of a human participant. The step-climbing experiment showed that feasibility of the proposed method to perform step-climbing stably with standing posture.

In conclusion, we confirmed that an overall COM position and designing mechanical power flow play an essential role for step, and stair-climbing mobility devices regardless of user's sitting and standing posture on a mobility device. Last, we described an answer to the research question based on all findings of this research.

6.1 Contribution of This Work

6.1.1 Contribution to Step/Stair-climbing Mobility Device

The main contribution of this research is to introduce the methodology to perform step/stair-climbing using user's capabilities such as upper body strength to the field of existing step/stair-climbing mobility devices focusing on mechatronics. This approach would help to realize long-term independent social life, especially for people who need to use assistive mobility devices such as wheelchairs. Also, this research shows guidelines as well as practical examples for designing future mobility devices for human centered assistive devices.

6.1.2 Contribution to Human Informatics

First, informatics is defined in Cambridge Dictionary as follows [103]:

- Informatics studies the structure, behaviour, and interactions of natural and artificial systems that store, process, and communicate information.

Based on the definition, human informatics is defined in this research as the study of structure, behaviour, and interactions of human and any systems that store, process, and utilize information.

The main contribution of this research to human informatics is to propose modelling methodologies which utilize physical interactions between human and machine in step/stair-climbing scenario.

The approach of this research would be able to help to design human centered assistive mobility devices which support human locomotion. Lots of countries, especially Japan are facing ultra aging society, which more people has limited capabilities in their daily life. For long-term healthy and independent social life, the proposed approach that makes use of human capabilities is beneficial and opens a new door for area of human informatics.

6.2 Future Directions

6.2.1 Application with Various Assistive Mobility Devices

In this research, we proposed a step/stair-climbing methodology using the overall COM position shifting and mechanical power flow. We implemented the method to a regular manual wheelchair so that the wheelchair users can perform step/stair-climbing by user him/herself. Also, we designed a step-climbing methodology for standing mobility devices. However, the fundamental methodology can be implemented with a various types of assistive mobility devices which physical interactions between human and machine occur. Possible candidates include walkers for an aged person, gait trainers, exoskeletons, and other similar mobility devices. Also, the method can be extended to any mobility devices for not only supporting people with lower limb impairment, but also augmenting locomotion capability of healthy persons.

6.2.2 Assistive Mobility Devices with Human and Machine

In this research, we only investigated manually operated, and powered step/stair-climbing mobility devices using the posture transition, the lever propelled, and the parallel elastic mechanism. However, utilizing human capability with machine must have other possibilities. We believe lever propelled mechanism is just one possible practical example. A power assisted mechanism is also one of possible candidates. Also, we did not check comfortability while operating the proposed mobility devices. Toward assistive mobility devices with human and machine, we must investigate possible physical interactions between human and machine, and their operability and comfortability. Yunfeng et al. proposed a design control system and power combination mechanism of a power assist system of the walking chair based on kinetostatic characteristics of human arm [104]. It also discussed comfortable driving feeling and efficient utilization of user power. With the all of findings, we will open a new academic area of assistive mobility devices with human and machine.

6.2.3 Mathematical Modelling of Step/Stair-Climbing with Human and Machine

Step and stair are one of the critical obstacles for locomotion. In this research, we showed a fundamental concept of step/stair-climbing with human and machine, and 3 practical examples. For taking a further step of this research, we will establish a methodology for mathematical modelling of step/stair-climbing with human and machine for not only calculating motion, but also understanding optimal mechanical elements and their connections. With the related works regarding mechanical power flow and physical interaction between human and machine [105, 106], we take on this challenge.

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