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Development of a Lightweight Powered Wheelchair for Persons with Physical Disabilities Using a Participatory Action Design †

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Abstract: We developed a basic lightweight powered wheelchair model using a participatory action design (PAD). We conducted two types of research to identify users' desires and satisfaction with wheelchairs: one focused on identifying the problems and needs of manual or powered wheelchair users through focus group interviews (FGIs), and the other focused on capturing users' post-experience feedback with the developed prototypes through usability testing (UT). We structured scenario-based usability tests and questionnaires to capture the participants' experiences and needs, with the results indicating that both manual and powered wheelchair users emphasized the product's lightness, design, cost, and battery and motor performance. This user-focused development resulted in higher satisfaction and usability. The significance of this study lies in the active involvement of wheelchair users throughout the research process, incorporating the obstacles and terrains they encounter in real community environments into the development. Future research should assess the usability of the final lightweight powered wheelchair, aiming to improve its affordability to wheelchair users through public benefits.

Keywords: assistive technology; focus group interview; lightweight powered wheelchair; participatory action design; usability testing

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1. Introduction

As of 2020–2021, mobility disadvantaged persons constitute 30% of the population in South Korea, with more than 5% (approximately 2,640,000 individuals) having disabilities [1]. An estimated 586,080 people with disabilities require mobility assistance in their daily lives, and people with physical disabilities comprise the highest proportion of those residing in communities [2,3]. For people with physical disabilities, the more severe the disability, the more difficult it is for them to move independently. Although activity support services help support the daily lives and social participation of people with mobility disabilities, professionals should provide mobility-assistive devices to help users live independently [4,5]. Thus, applying assistive technology (AT) is the first step toward ensuring free and independent mobility for people with disabilities, securing their right to mobility, and enabling them to live as social beings integrated and engaged with human and social resources around them [6,7].

The World Health Organization (WHO) systematically compiled a priority assistive product list of 50 items in 2016, including powered and manual wheelchairs, to guide

national support policies. Furthermore, the WHO is working to improve the affordability of quality assistive devices for users worldwide [6].

In South Korea, various assistive devices are subsidized by the National Health Insurance Service to reduce the burden on people with disabilities and their families. In 2023, approximately 68,441 USD was allocated for disability assistive device benefits, with powered wheelchairs and scooters accounting for 12.3% and manual wheelchairs for 5% of this funding. Wheelchairs supported by the National Health Insurance Service include standard powered wheelchairs, powered wheelchairs with additional seating options, and manual wheelchairs (standard, active, tilting, or reclining) [8]. While wheelchairs facilitate easier and more independent movements for users, powered wheelchairs are typically expensive, bulky, and heavy, limiting their transportation in personal vehicles, while manual wheelchairs have varied storage requirements, and their long-term use can lead to physical strain and damage, necessitating ongoing research on their management [9–14]. Efforts to address and improve the shortcomings of powered and manual wheelchairs have led to the development of manual/power hybrid wheelchairs and lightweight powered wheelchairs both domestically and internationally [15–17]. These hybrid wheelchairs, propelled manually or operated via a joystick, require less strength and stamina when manually propelling and integrating the motors, reducers, and brakes within the wheels [15,16]. Lightweight powered wheelchairs are defined by their reduced weight compared to standard powered wheelchairs, with the ability to switch between manual and power operation. These wheelchairs are often used as secondary wheelchairs for specific activities [18,19], necessitating design and development efforts tailored to the purposes of secondary wheelchairs.

Two considerations were suggested for the efficient development of assistive technology devices (ATDs) [20]. The first considers sustainable assistive technology services (ATSs). The essence of this approach is to design products within the context of the country and address all the necessary components, such as motors, controllers, and frames, to facilitate the development of powered wheelchairs. The second consideration is user participation, which is consistent with the definition of AT. AT integrates devices and services, emphasizing the development and provision that meet the needs of end users, enabling them to engage in the desired activities [20]. Similarly, the human activity assistive technology model describes AT as devices or services used within an individual's environment to facilitate activities. The application of AT is not just about providing ordinary devices based on eligibility but also about enhancing and considering the functional abilities of individuals with disabilities, allowing them to perform desired activities [20,21]. According to Bevilacqua, considering intrinsic capacity when designing technology-based interventions is important to support independent living for users, such as people with disabilities and the elderly. This approach means evaluating and incorporating physical abilities, such as mobility, and the user's goals and ability to adapt to daily life [22]; this approach is essential for providing AT. Thus, user-centered development and services are crucial. Participatory action design (PAD) methods, which evaluate stakeholder groups and integrate their feedback into the design and decision-making processes, are extensively used in AT research, highlighting the importance of active user participation [23–25]. This method aims to break down the barriers between researchers and users by including users in the design team [26].

This study aims to develop lightweight powered wheelchairs for wheelchair users in South Korea, particularly focusing on incorporating user feedback through focus group interviews (FGIs) and usability testing (UT). This approach goes beyond simply providing AT by playing a crucial role in ensuring technology is seamlessly integrated into users' daily lives.

2. Methods

This research, conducted with the support of the South Korean government, covered the entire process, from the development of the lightweight powered wheelchair prototype to the completion of the final product. Research on the development of the initial prototype has

been published in peer-reviewed journals in South Korea [13,27]. In this study, the research team continued the development process by conducting PAD research and incorporating real stakeholder feedback through FGIs and UTs to finalize the product (Figure 1).

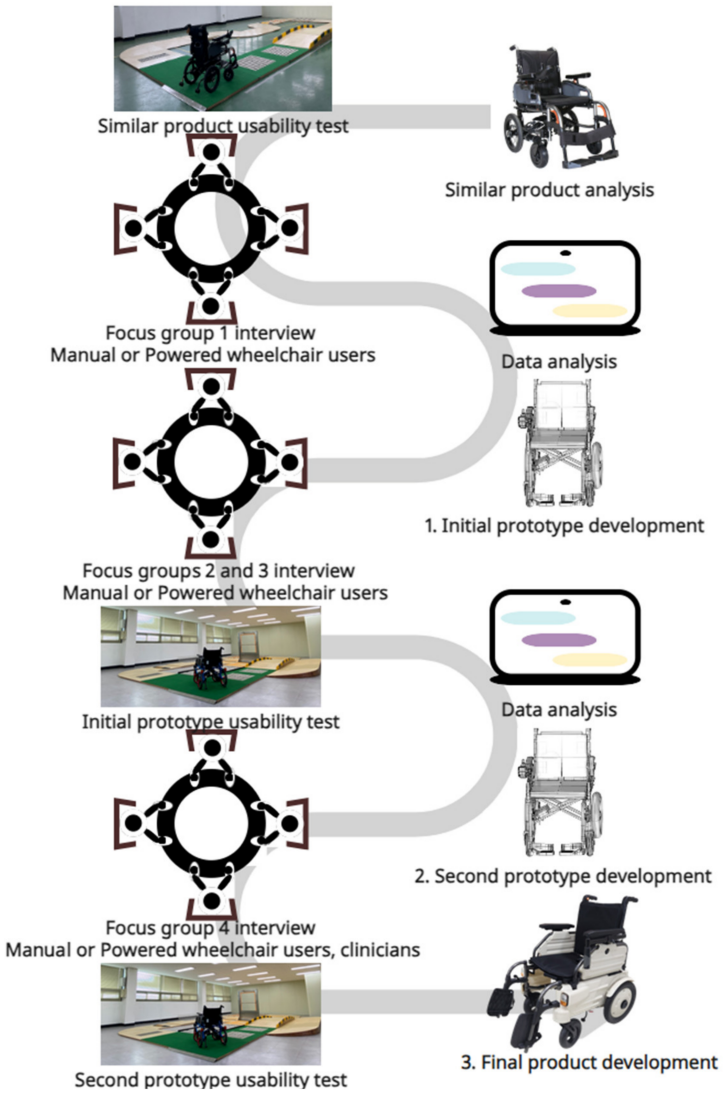


Figure 1. Study process.

2.1. Usability Testing (UT)

Indicators were constructed based on usability as defined by the International Organization for Standardization (ISO). According to the ISO-9241-11:2018 standard, usability includes effectiveness, efficiency, and satisfaction and refers to the quality felt by users when completing a specific task by utilizing a product within a context [28,29].

Effectiveness was measured based on task success, with efficiency assessed by measuring the effort and fatigue required when performing a task using the product through task performance time and the Borg rating of perceived examination scale (RPE), which ranges from 6 (no exertion) to 20 (maximum exertion). The subjective difficulty experienced while performing the task was measured through the difficulty rating scale (DRS), which ranges from −3 (very difficult) to 3 (very easy). Lastly, product acceptance, overall usability, and satisfaction were measured using the acceptability rating scale (ARS), which ranges from −3 (very unacceptable) to 3 (very acceptable), and the system usability scale (SUS).

Conducting UT requires developing a separate scenario that considers the ATD's function and task performance environment; therefore, interviews were conducted with wheelchair users living in the community to determine the driving environment that can be

experienced when moving around the community. By analyzing the collected information and interface for using the lightweight powered wheelchair, 18 tasks were derived along with three scenarios: setting, driving, and finishing [30]. The derived UT scenarios are listed in Table 1.

Table 1. Scenario for usability testing (UT).

Scenario	Task Number	Task	Initial Prototype	Revised Prototype
S1_Setting	S1_Task1	Connecting the developed four-part cushion	X [1]	O [2]
	S1_Task2	Connecting a battery	X	O
	S1_Task3	Turn on the wheelchair, adjust the speed	O	O
S2_Driving	S2_Task1	Driving on a sidewalk block	O	O
	S2_Task2	Driving on a 1/8 slope way	O	O
	S2_Task3	Driving on curbs	O	O
	S2_Task4	Driving on a bumpy road	O	O
	S2_Task5	Driving on a hollow road	O	O
	S2_Task6	Driving on a S type road	O	O
	S2_Task7	Driving on a steep slope way	O	O
	S2_Task8	Driving on a speed hump	O	O
	S2_Task9	Driving on a drain	O	O
	S2_Task10	Driving on a gravel road	O	O
	S2_Task11	Driving through the doorway	O	O
	S2_Task12	Driving on a braille block	O	O
	S2_Task13	Driving on a side slope way	O	O
S3_Finishing	S3_Task1	Turn off the wheelchair at the arrival point	O	O
	S3_Task2	Disconnecting the battery	X	O

[1] Task not performed with the prototype. [2] Task performed with the prototype.

2.1.1. Participant Selection for UT

In this study, a total of three usability tests were conducted to develop the final product. However, the UTs of foreign lightweight powered wheelchairs used to develop the initial prototype were excluded, and only two UTs were conducted. Participants were recruited through convenience sampling from people with physical disabilities who used manual or powered wheelchairs. Based on Nelson's study, five participants who agreed to participate were selected for each study, resulting in a total of ten participants [31]. Participants with disabilities were screened based on the following inclusion criteria: older than 18 years, community-dwelling, use of a manual or powered wheelchair for mobility, and no communication restrictions during the consent process. The exclusion criteria were not currently using a wheelchair or having involuntary movements.

2.1.2. Study Tools for UT

Lightweight Powered Wheelchair

The developed lightweight powered wheelchair, designed to allow easier battery detachment than standard powered wheelchairs, features an X-bar frame structure under the seat, which enhances foldability for storage and portability in vehicles. This wheelchair was developed by considering the challenges faced by people with physical disabilities when using manual or powered wheelchairs and their specific needs. Additionally, it can switch between manual and powered wheelchair operations depending on the terrain, such as flat surfaces or slopes (Figure 2).



(**a**) (**b**) (**c**)

Figure 2. Lightweight powered wheelchair: (**a**) Initial prototype. (**b**) Revised Prototype A. (**c**) Revised Prototype B.

Kit for Lightweight Powered Wheelchair Driving

We replicated scenarios that wheelchair users might encounter in the community based on the opinions of wheelchair users residing in the community and organized them into 13 different tasks according to the derived "driving" scenario (Table 1). The initial course layout used for analyzing the usability of similar foreign lightweight powered wheelchair products was constructed from wooden structures measuring 1.2 m by 1.2 m, creating a course 4.8 m wide and 10.8 m long, and was composed of 10 tasks. The improved driving kit was refined by adding obstacles for the UTs of the first and revised prototypes, ultimately extending the course to 6 m in width and 10.8 m in length, comprising 13 tasks (Figure 3a,b).



(**a**) (**b**)

Figure 3. Kit for lightweight powered wheelchair driving: (**a**) Initial kit, which includes 10 obstacles and terrain; (**b**) revised kit, which includes 13 obstacles and terrain.

Four-Part Off-Loading Cushion

The four-part off-loading cushion was primarily used to prevent pressure ulcers, a major complication for wheelchair users who need to sit for extended periods, and secondarily, to provide body stability when using a lightweight powered wheelchair. To enable faster and more convenient production compared with the traditional 100% customized manufacturing approach, cushions were designed based on data to fit the Korean body type, shaped through CNC machining, and then divided into four parts based on the protruding hip and coccyx. A pressure-mapping device was used to monitor and adjust the seated pressure, with the cushion modules secured in the optimal position for assembly (Figure 4).

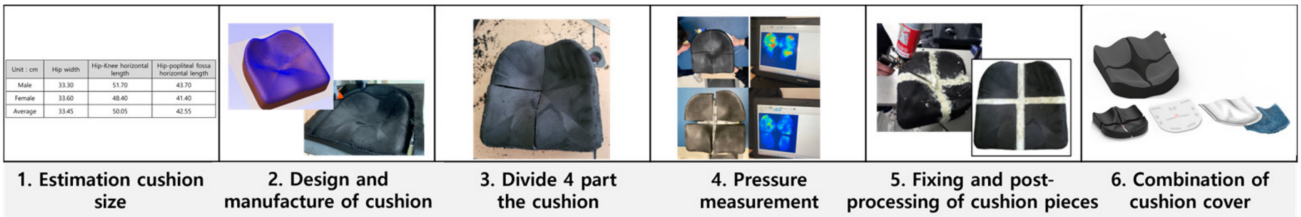


Figure 4. Four-part off-loading cushion development process.

2.1.3. UT Procedure

Two UTs, each lasting one day, were conducted at a research facility located in Gimpo, Gyeonggi-do, South Korea. The participants followed a four-step process during the study. First, they received an explanation of the purpose and procedure of the UT from the lead conductor and provided their consent before proceeding to the interview. Second, the participants were given detailed instructions on how to operate the prototype lightweight powered wheelchair and navigate the driving course, which included 15 tasks from the driving scenario. The participants were also allowed approximately 5 min to maintain a stable condition before beginning the actual tasks. Third, under the guidance and supervision of assistant conductors, the participants performed the tasks. Finally, after completing the course, they responded to post-interview questions (Figure 5).

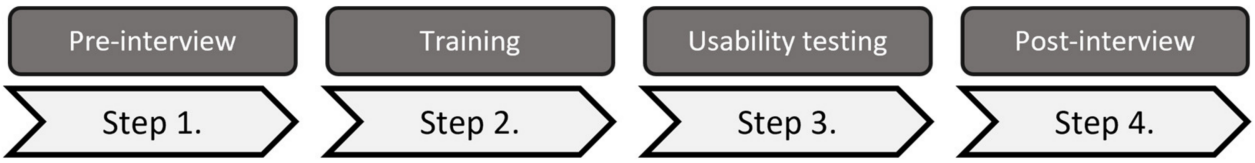


Figure 5. Usability testing (UT) process.

2.2. Focus Group Interview (FGI)

FGI is a qualitative research method for the in-depth exploration of user needs. By forming focus groups with common characteristics, researchers can better understand participants' experiences and thoughts [32,33]. Conducting FGIs throughout the research process helps identify user needs and collect more specific feedback, making FGIs essential from the early to later stages of research in AT [34]. With user input crucial in the development of assistive devices, FGIs were conducted to analyze the opinions of manual and powered wheelchair users and clinicians, among other stakeholders, and incorporate these insights into the development of lightweight powered wheelchairs. This study included only the research processes conducted after the development of the first prototype and excluded the FGIs conducted to develop the initial prototype.

2.2.1. Participant Selection for FGI

While the typical guideline for an appropriate number of participants in an FGI is 6–12, this criterion cannot be absolute considering the actual participation and capabilities of the participants; hence, this study included 5 or 6 participants per stakeholder group [35,36]. All participants, recruited through convenience sampling, were people with physical disabilities who used manual or powered wheelchairs. All FGI sessions with individuals with disabilities were conducted twice between December 2021 and January 2022, and interviews with clinical experts were conducted in October 2022. The clinical expert group consisted of one individual with medical knowledge and four rehabilitation experts, including occupational and physical therapists. Participants with disabilities were screened for the following inclusion criteria: age between 18 and 65 years, community-dwelling, use of a manual or powered wheelchair for mobility, use of an offloading cushion for pressure ulcer prevention, and without communication restrictions during the consent process. Clinical experts were selected according to the following criteria: professionals with knowledge of rehabilitation, occupational therapy, or physical therapy and experts with experience in treating, educating, training, or researching wheelchair users with disabilities.

2.2.2. Study Tools for FGI

Questionnaire for Interview

In this study, the questionnaire for the FGI was pre-constructed, with the initial draft of the questions based on the literature by the lead conductor and finalized through discus-

sions with assistant conductors. The questions were categorized as opening, introductory, transitional, key, and ending [32].

2.2.3. FGI Procedure

Three group interviews led by an experienced researcher (lead conductor) were conducted and recorded online using the Zoom platform (Zoom Video Communications, Inc., San Jose, CA, USA. Version 6.1.12). The FGIs were held online to address safety concerns for participants and restrictions on inter-regional travel due to the COVID-19 pandemic and facilitate participation from stakeholders in various regions. Internet connectivity and ambient noise levels were checked in advance to ensure a smooth interview process. Each group interview was conducted for 60–100 min, providing visual information through presentations after explaining the research purpose and obtaining consent. The recordings from each FGI were transcribed using the transcription feature of CLOVA Note and subsequently reviewed by researchers to enhance accuracy.

2.3. Data Collection and Analysis

All study procedures were approved by the university's Institutional Review Board (1041849-202103-BM-032-02 and 1041849-202303-BM-055-04). Written informed consent was obtained from all participants before their participation. In addition, the participants were compensated for their participation in the study.

2.3.1. UT

Effectiveness, efficiency, and satisfaction were assessed through post-hoc interviews. Task success was determined by calculating the ratio of successful tasks to the total number of attempts per wheelchair (100% = 1 attempt, 1 success). Performance time, RPE, DRS, ARS, and SUS were calculated using Microsoft Excel to obtain average scores and standard deviations, all presented in the tables and charts. The collected qualitative data focused on the UX and suggested improvements, as discussed by the research team.

2.3.2. FGI

The notes and transcribed data collected through the FGI were organized into a single file and analyzed according to the six-phase criteria proposed by Braun and Clarke [37]. These phases include becoming familiar with the data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing reports. Researchers independently coded the organized files line-by-line using Atlas.ti 24 software (ATLAS.ti Scientific Software Development GmbH, Berlin, Germany. Version 24) to facilitate coding. Additionally, to enhance the reliability and validity of the research, the researchers conducted crosschecks during the theme review phase, harmonized opinions through discussions, and reviewed the responses with the participants to ensure that no distortions or omissions occurred.

3. Results

3.1. Initial Prototype Development

The initial prototype was developed using one round of the UT and one FGI. The usability and satisfaction of five participants were analyzed based on the SUS score, which resulted in a score of 75.2, rated as Grade B/"Good". This score and rating were set as the minimum standard for the usability of the final product. Based on this analysis, the initial prototype was designed and manufactured. However, some structural parts were changed during the refinement process, considering the product's lightness, cost, and design (Figure 6).

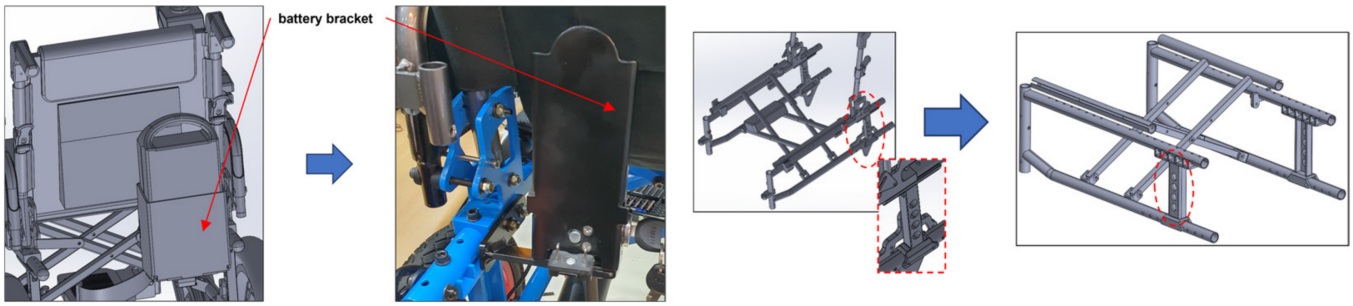


Figure 6. Initial prototype: (**a**) change in battery bracket to save weight; (**b**) simplification of frame support (from die casting method to bending method).

3.2. UT of Initial Prototype

3.2.1. General Information of Participants for Initial Prototype UT

Of the five participants, four were male and one was female, with an average age of 50.2 years. All five participants had been diagnosed with spinal cord injuries (SCIs); specifically, four had thoracic injuries and one had a cervical injury. The average duration of disability among the participants was 27.2 years, and their primary wheelchair type was the manual wheelchair (Table 2). All the participants were capable of independently propelling their wheelchairs, both indoors and outdoors. Only two participants had experience using lightweight powered wheelchairs during travel and out of curiosity.

Table 2. General characteristics of five participants.

No	Sex	Age	Diagnosis	Duration of Disability	Primary Wheelchair
P1	Female	60	Spinal Cord Injury	37	Manual Wheelchair
P2	Male	57	Spinal Cord Injury	52	Manual Wheelchair
P3	Male	42	Spinal Cord Injury	16	Manual Wheelchair
P4	Male	44	Spinal Cord Injury	20	Manual Wheelchair
P5	Male	48	Spinal Cord Injury	11	Manual Wheelchair

3.2.2. Usability and Satisfaction of Initial Prototype

The analysis of participants' responses revealed that tasks requiring at least some effort were identified as "Driving on curbs", "Driving on a hollow road", "Driving on a speed hump", "Driving on a gravel road", and "Driving on a side slope way"; these five tasks were also relatively more challenging. According to the interview results, these tasks were related to the power of the powered wheelchair, the size of the wheels, and accessories. Nevertheless, the participants indicated they could accept all the tasks (Table 3).

The analysis of overall satisfaction and usability for the initial prototype among all participants resulted in a score of 74.4, rated as Grade B/'Good," interpreted as sufficiently acceptable, with participants feeling a level of satisfaction that, while not enthusiastic, is sufficient to recommend the product to others [38] (Figure 7). However, in this study, the initial prototype exhibited a lower usability score than the minimum usability standard (75.2 in this study).

Table 3. Results of the initial prototype's usability.

Task	TPT [1] (Aver./SD)	RPE [2] (Aver./SD)	DRS [2] (Aver./SD)	ARS [2] (Aver./SD)
S1_task3	7.6/2.61	6.00/0.00	3.0/0.00	3.0/0.00
S2_task1	4.9/0.74	7.00/1.22	1.8/1.30	2.2/1.30
S2_task2	7.3/1.30	7.20/1.10	1.8/1.10	1.0/1.00
S2_task3	6.8/2.95	11.8/0.84	−0.4/0.89	0.0/1.22
S2_task4	5.4/1.14	7.4/2.19	1.2/1.30	1.6/0.89
S2_task5	6.4/4.28	11.6/2.97	−0.4/1.14	0.2/1.30
S2_task6	2.8/0.84	6.6/0.55	2.6/0.55	2.6/0.55
S2_task7	4.0/0.71	7.6/1.34	1.2/1.30	1.6/1.14
S2_task8	14.4/11.63	13.8/1.30	−0.6/0.89	0.0/1.00
S2_task9	3.0/0.71	7.0/1.41	1.2/1.64	1.4/1.34
S2_task10	6.2/1.79	11.4/3.36	−0.6/1.14	0.4/1.34
S2_task11	9.6/2.30	9.0/3.54	0.2/1.64	1.0/1.22
S2_task12	6.0/1.87	6.4/0.55	1.6/1.52	1.6/1.52
S2_task13	10.0/2.24	11.4/4.04	0.4/2.41	0.8/1.79
S3_task1	2.8/0.45	6.2/0.45	2.0/1.22	2.0/1.22

[1] Task performance time (TPT) is measured in seconds (s). [2] The unit of rating of perceived examination scale (RPE), difficulty rating scale (DRS), and acceptability rating scale (ARS) is points.

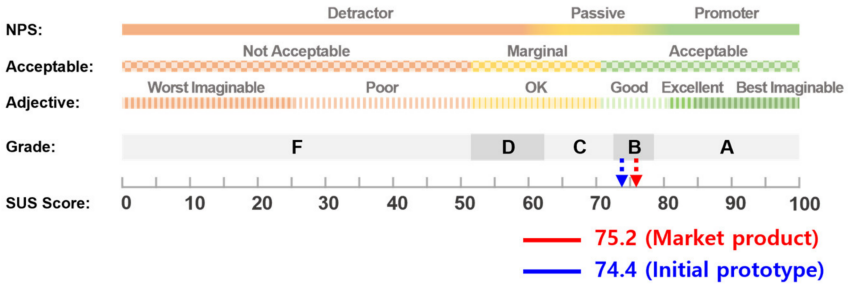


Figure 7. Results of the initial prototype's SUS.

3.3. Revised Prototype Development

The revised prototype was refined by incorporating feedback from the two-wheelchair user group interviews to reflect the usability of the initial prototype. The first group consisted of users who owned a manual/power hybrid wheelchair, while the second group consisted of users who used a customized pressure ulcer prevention cushion. Five manual/power hybrid wheelchair users participated in group interviews. They used manual/power hybrid wheelchairs for daily living and participating in activities within their homes, and their reasons for purchasing these manual/power hybrid wheelchairs included the power of the motor, the convenience of battery detachment, the ability to load the wheelchair into a vehicle, stability, safety, and compensation for physical functions. Despite experiencing difficulties with the lightness of the wheelchair and the obstructions caused by the caster wheels during obstacle driving, the FGI participants expressed a desire for even lighter and smaller wheelchairs, as well as the need for safety during braking and comfort when sitting. Some of the responses from the FGI participants are provided below.

"I needed a wheelchair that could be easily placed in a car and used indoors, and using a manual/power hybrid wheelchair has allowed me to live independently at home and move around outdoors without any help from my family. Using a manual wheelchair often damaged my shoulders, but now I can engage in more activities... Most importantly, I wish the wheelchair were lighter. I feel so sorry when I need help from my family or others". (manual/power hybrid wheelchair user, Participant 1; Participant 2)

"For me, I chose the manual/power hybrid wheelchair because it's easier to take on planes, and the manual/power hybrid wheelchair feels stable as it stops well when I need it to due to the engine brake. Safety needs to be considered more when developing these wheelchairs... As the wheelchair gets lighter, it can be pushed by the user's weight. You have to be careful with the brakes". (manual/power hybrid wheelchair user, Participant 3)

"I had to consider purchasing one for overseas travel for performances, and I chose the current product because it has strong motor power and good stability. And most importantly, the battery is very easy to detach... The current wheelchair weighs 35 kg, which is too heavy, and even men are surprised when I ask for help. Also, using it for a long time puts a strain on my back". (manual/power hybrid wheelchair user, Participant 4; Participant 5)

The group using a customized pressure ulcer prevention cushion included six users who used their wheelchairs for between 8 and 17 h daily; five were powered wheelchair users, and one used a manual wheelchair. The participants were highly satisfied with the improvement in pressure ulcers using customized cushions, commonly expressing the need for washable and waterproof covers. Difficulties with cushion transport and vehicle access were noted as problems. Many concerns have been raised regarding a ready-made pressure ulcer prevention cushion that creates a pressure ulcer prevention cushion of standardized size according to the wheelchair user's body shape and adjusts it to suit the user, making it challenging.

"Because some wheelchair users leak urine or make mistakes, so I think the customized pressure ulcer prevention cushion needs waterproof materials. Otherwise, it takes a long time to dry completely after washing". (Customized cushion user, Participant 4; Participant 5; Participant 6)

"I like that the pressure points go away after using the cushion... Customized pressure ulcer prevention cushion is high, making it difficult to use paratransit services. Sometimes my head touches the roof of the vehicle... I'd like to try ready-made cushions as they could save time, but the best choice would be a completely customized cushion". (Customized cushion user, Participant 1)

"Moving a customized pressure ulcer prevention cushion from one wheelchair to another can be difficult, and the cushion's height makes vehicle use uncomfortable... I think trying a ready-made pressure ulcer prevention cushion could be worth it, but I'm worried it might not fit depending on the type of wheelchair, and if attempted, various sizes of ready-made cushions would be needed". (Customized cushion user, Participant 2)

"Using a customized cushion has reduced skin peeling and eliminates pressure ulcer, allowed me to sit in the wheelchair for longer periods... I believe it's important for ready-made pressure ulcer prevention cushion to be made to fit the user's body shape". (Customized cushion user, Participant 5)

"I found the effect of the customized pressure ulcer prevention cushion to be very good. I think a ready-made pressure ulcer prevention cushion could also be good if various sizes are developed considering the user and the wheelchair. I would prefer if the price were a bit lower". (Customized cushion user, Participant 6)

Participants at the UT of the initial prototype reported difficulties, particularly with speed humps and hollow roads, and challenges when driving on side slopes, gravel roads, and curbs. The advantages of the initial prototype include the ability to independently drive over obstacles and terrain without the assistance of a caregiver, ease of operation, lightness compared with a standard-powered wheelchair, and the ability to be loaded into a vehicle. However, compared to foreign products, there were issues regarding durability and design, difficulty in detaching the battery, and reduced stability due to the low weight. Concerns have been raised regarding the potential limitations of independent propulsion and mobility with lightweight-powered wheelchairs, and users who tested the initial prototype mentioned the need for improvements in battery capacity, design, stability, convenience, and compensation for physical functions, all of which are decisive factors in purchasing the product.

> *"When driving on a speed hump, it was difficult if the speed was too slow, but manageable when I speed up. Also, if the flat surfaces had been a bit longer, the task would have been easier". (UT Participant 1 and Participant 2)*

> *"Driving on a hollow road was quite challenging. The wheels need more elasticity, and a bit more motor's power would have made it easier... If the battery capacity were larger and the design improved, I would consider purchasing it". (UT Participant 1)*

> *"Side slope, hollow, and gravel roads were quite difficult. Besides the performance of the wheelchair, there was a psychological unease about the terrain... Using a lightweight powered wheelchair would especially make long-distance travel more convenient". (UT Participant 3)*

> *"The prototype felt less stable as it was smaller and lighter. I would prefer if it were a bit lower to the ground, and it would be helpful to have a structure on the opposite side of the primary hand that could be grasped... Using a lightweight powered wheelchair could complement physical functions and reduce fatigue". (UT Participant 4)*

> *"There were particular difficulties when moving over curbs, and it would likely be more challenging outdoors... More than anything else, I appreciated that it was fitted with an offloading pressure ulcer prevention cushion". (UT Participant 5)*

> *"The initial prototype seems weaker compared to foreign products, and its appearance lacks distinctiveness and style". (UT Participant 1 and Participant 5)*

3.4. UT of Revised Prototype

The test followed the same procedures and environment as the UT for the initial prototype. The UT for the revised prototype involved completing 18 tasks structured around three scenarios: setting, driving, and finishing. Compared with the tasks for the initial prototype UT, tasks involving a cushion and battery detachment were added and performed with the assistance of the caregivers.

3.4.1. General Information of Participants for Revised Prototype UT

All five participants were male, with an average age of 58 years. Four participants were diagnosed with SCI, two with cervical injuries, and two with thoracic injuries, and the remaining participants had poliomyelitis. The average duration of disability among the participants was 36 years. The primary type of wheelchair used was a powered wheelchair for four participants, and one participant used a manual wheelchair with a power-assisted unit (Table 4). All participants, accompanied by a personal assistant with disabilities, were capable of independently propelling their wheelchairs both indoors and outdoors. Three participants reported having experience with lightweight powered wheelchairs and using them for travel, vehicle loading, and receipt through support projects.

Table 4. General characteristics of the five participants.

No	Sex	Age	Diagnosis	Duration of Disability	Primary Wheelchair	Caregiver
P1	Male	53	Spinal Cord Injury	25	Powered	Personal Assistant
P2	Male	59	Spinal Cord Injury	54	Powered	Personal Assistant
P3	Male	45	Spinal Cord Injury	26	Powered	Personal Assistant
P4	Male	68	Poliomyelitis	67	Power assist	Personal Assistant
P5	Male	65	Spinal Cord Injury	11	Powered	Personal Assistant

3.4.2. Usability and Satisfaction of Revised Prototype

The analysis of the participants' responses revealed that tasks such as "driving on curbs", "driving on a gravel road", and "driving on a side slope" required more effort, with "driving on curbs" and "driving on a gravel road" being relatively more difficult and having lower acceptance. Overall, revised Prototype A required more effort, was more difficult, and had lower acceptance than revised Prototype B. However, in tasks performed by wheelchair users, such as driving over the drain, passing through doorways, and driving over braille blocks, revised Prototype B was more difficult and had lower acceptance than Prototype A. Additionally, in the battery attachment task performed by caregivers, Prototype B showed greater difficulty and lower acceptance than Prototype A (Figure 8).

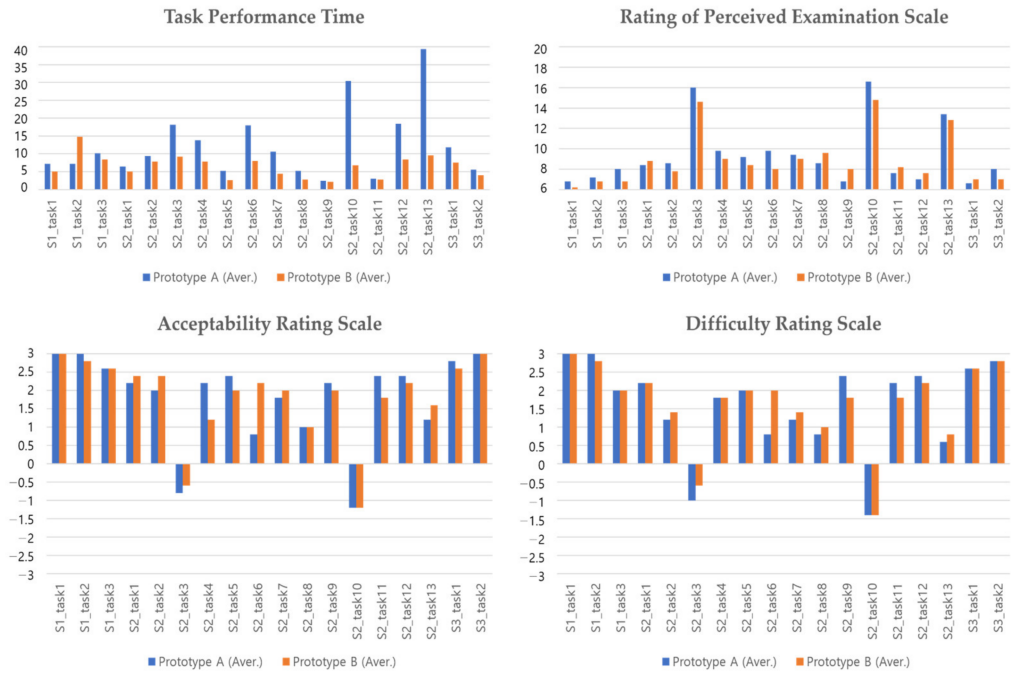
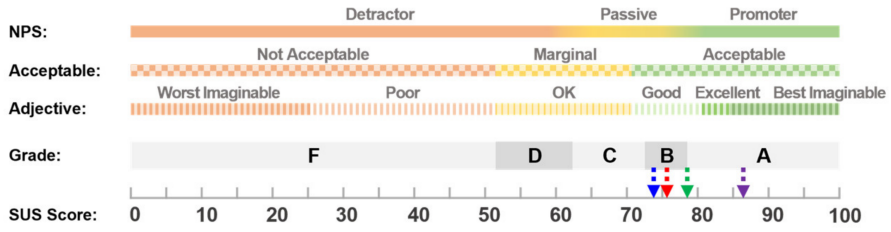


Figure 8. Results of the revised prototype's usability.

The overall satisfaction and usability of revised Prototypes A and B were evaluated using the SUS score and compared with the SUS scores of both the foreign product and the initial prototype. The SUS scores of all four products should be above 71.1 points for acceptable usability [39]. All products scored above 71.1 points, with Prototype A scoring 77.6 and Prototype B scoring 86.4 (Figures 8 and 9), signifying a Grade B/"Good" and Grade A/"Excellent" level of usability, respectively, both exceeding the foreign product's SUS score of 75.2, which serves as the minimum usability standard in this study. Notably, Prototype B received a Net Promoter Score rating of "promoter," indicating a high likelihood of being recommended to others [38] (Figure 9).



	Product	Average	Minimum	Maximum
	Market product	75.2	68	86
	Initial prototype	74.4	68	84
	Revised prototype A	77.6	66	86
	Revised prototype B	86.4	76	98

Figure 9. Results of the revised prototype's SUS.

3.5. Technical Characteristics of Lightweight Powered Wheelchair

The final product was developed based on the UT results of the revised Prototypes A and B and the user feedback derived from the FGI (Figure 10).



Figure 10. Lightweight powered wheelchair: Final product.

The development of the final product focuses on weight reduction, size, motor power, and design. First, adjustments were made to the weight and size. According to the width/depth/height (cm), revised Prototype A was 58/105/84, and revised Prototype B was 58/103/96. Some participants in the UT commented that revised Prototype B, although usable overall, including the installed safety bars, was too large. Conversely, revised Prototype A was rated lower in usability but was considered appropriately sized. Based on these outcomes and feedback, the dimensions of the final product were adjusted by reducing the overall height and axle distance to 56/97/86. The reduced size allowed for the installation of safety bars, improvements in design and motor output, and the use of a lithium-ion battery to further reduce the weight (Table 5).

Table 5. Specifications of the final product.

Specification	Value	According To
Width/Depth/Height (cm)	56/97/86	Usability testing
Mass (kg)	32	User's opinion
Mass without Battery (kg)	28	User's opinion
Battery (Wh)	816	User's opinion
Max distance (km)	25	User's opinion
Motor power (W)	250 × 2	Usability testing

4. Discussion

This study was conducted with the support of the South Korean government from 2020 to 2023 to improve the quality of life of people with disabilities and respond to the expanding market for mobility-assistive devices due to societal aging. Additionally, the study was conducted in response to the growing need for research on powered wheelchairs and scooters in Korea and the necessity to develop domestic products to address the durability and cost issues associated with imported products. The entire research process was conducted using PAD methods to evaluate and gather feedback from actual users to develop an ATD that enhances user satisfaction, aligning with the definition of AT that should serve individual activities and needs. Two UTs and two FGIs were conducted to develop a lightweight powered wheelchair for 17 manual or powered wheelchair users. Their caregivers, medical professionals, and rehabilitation specialists participated in the study. Similar methodologies were employed in Giesbrecht's study, which developed a home wheelchair skills program for the elderly through repetitive user evaluations and interviews, optimizing the tablet interface to deliver more intuitive information and making it more acceptable to users [24]. Additionally, Pearlman et al. examined user experiences in different national contexts to identify the improvements and strengths of prototypes, leading to the development of an enhanced product [40]. The continuous development of user-centered ATD and ATS is essential.

To develop the initial prototype, UTs and FGIs were conducted on foreign products. Positive feedback was received, with areas for improvement identified through user feedback. This wheelchair was praised for its easy battery detachment, compact size, and foldability, which offered greater portability and stability during operation than other powered wheelchairs. However, there have been suggestions for improvements in the sturdiness and lightness of the wheelchair frame, sufficient battery capacity, intuitive controls, wheel size, reinforcement of caster wheels, backrest and seat enhancements, and detachability and robustness of armrests [13,27]. Considering the strengths and improvements of foreign products, an initial prototype was developed, with its usability tested with five manual wheelchair users. During the test, task S2–task 8 (driving on a speed hump) required a particularly long time period. In subsequent interviews, participants explained that this long time period was due to a lack of flat terrain after descending a steep slope and not due to the wheelchair's performance. They noted that the task could be completed faster by increasing the driving speed during the retry. Based on these findings, the UT of the revised Prototypes A and B adjusted the speed hump and drain sequences.

The UT for revised Prototypes A and B involved five users of powered wheelchairs and power-assisted wheelchairs, along with their caregivers. The main differences between Prototypes A and B include variations in wheelchair specifications and battery attachment methods. Moreover, the accessories were adjusted based on feedback from the UT and FGI results of the initial prototype. Prototype A was developed in a smaller size than Prototype B, excluding the support handles, and using a box-type battery attachment method that required only vertical force for attachment. In contrast, Prototype B was developed with a slightly larger size, included support handles, and used a bracket system for battery attachment that required both vertical and diagonal forces to reduce the weight. The results showed that users and caregivers felt Prototype A was more compact and were relatively satisfied with its battery attachment method, considering it acceptable and easy,

whereas Prototype B received positive feedback for its supporting handles, which enhanced overall user satisfaction. Thus, Prototype A may be preferred for caregiver satisfaction, whereas Prototype B may be preferred for user satisfaction. However, both prototypes were similarly reported to cause discomfort owing to the pressure ulcer preventing the cushion, which ranged from 1 cm at the lowest point to 6 cm at the thickest point. Pressure ulcers are common complications in individuals with spinal cord injuries that significantly hinder social activities and daily living, making prevention and management crucial [41]. The pressure ulcer-preventing cushion, designed based on the body shape of wheelchair users, is a prefabricated version of a custom offloading cushion. The offloading cushion, which has provided positive clinical and economic outcomes, was used to distribute pressure on the buttocks while seated [41,42]. Although this cushion was designed based on feedback from clinical experts and cushion users, feedback from participants in UT and FGI indicated that additional research is needed to assess how adjustable the height is and how well it can be customized for individual users. To address these issues, further research is planned to explore methods for directly attaching a cushion to a frame and reducing its height.

In this study, manual wheelchair users emphasized the importance of a lightweight design and portability, whereas powered wheelchair users prioritized reduced weight and stability. Manual wheelchair users highlighted these aspects to facilitate handling of the wheelchair by themselves or their caregivers, whereas powered wheelchair users stressed the need for reduced weight to ease the burden on caregivers while also emphasizing stability, particularly concerns about wobbling or the risk of tipping over during use. These responses are consistent with those reported in previous studies [13,43,44].

According to Cooper et al. [9], wet-cell lead-acid batteries exhibit the best performance and are the least expensive. However, the lightweight-powered wheelchair developed in this study, while considering the cost of reducing the financial burden on family members purchasing the product, also recognizes a significant weight difference compared to standard-powered wheelchairs. Assuming its use as a secondary wheelchair for specific activities on a temporary basis, it incorporates lithium-ion batteries, which are lighter and allow relatively longer distances to meet user needs.

Future research should measure and present the societal value created using lightweight wheelchairs. In Sweden, studies have demonstrated that using powered wheelchairs and scooters by the elderly and people with disabilities is economically beneficial. Currently, in Korea, powered wheelchairs are supported once every six years with a funding cap. Moreover, for funding eligibility, the product must be registered with a support agency, meaning that lightweight-powered wheelchairs must be developed and registered before users can receive financial assistance to purchase them. Users of powered wheelchairs in Korea will then have to decide whether to use the opportunity to receive support every six years to purchase a lightweight powered wheelchair. The economic and social value of lightweight-powered wheelchairs is expected to be sufficient to warrant their provision.

The first limitation of this study was the limited scope of interview participants. In South Korea, the use of lightweight powered wheelchairs remains uncommon; therefore, FGI 1 consisted of end users who were manual/power hybrid wheelchair users, and Group 2 comprised manual or powered wheelchair users who had experience using a customized pressure ulcer prevention cushion.

The second limitation relates to the generalizability of the FGI and UT results. Although the focus groups in this study were based on previous research, the number of participants was limited. Therefore, the results do not represent the opinions of all manual or powered wheelchair users. Future research should involve more frequent feedback collection through focus groups segmented by wheelchair user characteristics and examine possible differences in wheelchair usage environments depending on the region in South Korea.

Third, there were limitations in providing sufficient experience with lightweight-powered wheelchairs. In this study, each participant had ample time scheduled between sessions and received adequate training before the tests; however, conducting each UT within a single day limited the depth of experience provided. Additionally, the driving kit

was set up on the second floor of the research facility, which constrained space availability; consequently, the driving tasks for the lightweight powered wheelchair were replicated with short obstacles and terrain; thus, stability during fast driving and sudden stopping was not fully tested.

The usability of the final product, developed based on the usability and user feedback of the revised prototype, has not yet been confirmed and hence will serve as a foundation for future research on lightweight powered wheelchairs in Korea.

The study was significant in that it focused on user experience and needs and demonstrated high satisfaction and usability scores by developing products that meet user needs. We hope that powered wheelchairs, currently under review for medical device approval by the Korea Food and Drug Administration, will enter the domestic market and be distributed to powered wheelchair users in South Korea.

5. Conclusions

A basic lightweight powered wheelchair model was successfully developed using the PAD process. UTs and FGIs were conducted to involve users, with their feedback incorporated to refine the lightweight wheelchair. The final product is currently undergoing medical device approval by the Korea Food and Drug Administration. After approval, aggressive marketing is expected to help it enter the powered wheelchair market and be available to domestic wheelchair users with disabilities through public benefits.

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Data Availability Statement: The data presented in this study are available upon request from the corresponding author. The data are not publicly available by default and are provided only after receiving approval from the relevant authorities.

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