Master's Thesis

Design of Sliding Footplate Manipulation Structure for Reducing Physical Demand in an Indoor Personal Mobility Vehicle

Yoonjoung Kwak

Department of Design

Ulsan National Institute of Science and Technology

2023

Design of Sliding Footplate Manipulation Structure for Reducing Physical Demand in an Indoor Personal Mobility Vehicle

Yoonjoung Kwak

Department of Design

Ulsan National Institute of Science and Technology

Design of Sliding Footplate Manipulation Structure for Reducing Physical Demand in an Indoor Personal Mobility Vehicle

Yoonjoung Kwak

This certifies that the thesis of Yoonjoung Kwak is approved.

07.03.2023 of submission

Signature

이희승

Advisor: Hui Sung Lee

Signature

KwanMyung Kim

Signature

Young-Woo Park

Abstract

This paper aims to explore methods for improving usability and operation demand of the indoor personal mobility vehicle AngGo and propose an enhanced design. While foot-operated controls have been studied in various interaction domains, research on foot-based operation in personal mobility vehicles is limited, with most personal mobility vehicles adopting hand-operated methods. The shared indoor smart mobility (SISM), AngGo features scenarios involving both autonomous and manual driving, with foot-operated controls incorporated in the manual driving mode. However, during various experiments and demonstrations conducted with AngGo, issues regarding physical demand associated with footplate manipulation were identified. To determine the improvement direction for AngGo, evaluations and interviews were conducted with a small group of designers to identify the factors that contribute to physical demand. Based on the interview results, modifications to the mobility vehicle's size and footplate design were adopted as approaches to reduce physical demand. Ergonomic specifications suitable for seated mobility vehicles were investigated, and an improved design was proposed, along with the design of a compact internal mechanical structure. A usability evaluation was conducted, comparing the revised design with the original design through experiments using a functional prototype, aiming to validate whether the user experience is enhanced. The results demonstrated that the revised design significantly reduced physical demand and effort. This study enhances the usability of AngGo through the improved design and provides reference data for ergonomic specifications in seated personal mobility vehicles. Additionally, the compact internal structure enables more diverse form designs for AngGo.

Contents

List of Figures

I Introduction

1.1 Background

Recently, personal mobility vehicles (PMVs) such as electric scooters and electric kickboards can be easily seen on the streets. These PMVs are also referred to by various names such as e-mobility vehicles, micro-mobility vehicles, and last-mile mobility vehicles. Revenue in the E-Scooter-sharing segment is projected to reach ₩2,419.00bn in 2023 and is expected to show an annual growth rate (CAGR 2023-2027) of 12.68% [Sta,]. With the growth of the mobility market, various types of PMVs have emerged, and the popularity of micro-mobility has increased steadily, especially with the introduction of shared e-scooter services in 2017 [Fitt and Curl, 2020].

This concept of the last mile can be indoors as well as outdoors. There are spaces and situations around us that are difficult to walk indoors. For example, in a huge airport, the distance to the gate is long and there is a lot of luggage, so walking can be burdensome. In convention centers, there are cases where people walk for a long time while watching exhibitions or participating in events. Most mobility vehicles are primarily designed for outdoor use, and there is limited research on indoor mobility vehicles. However, these indoor spaces can serve as potential areas of opportunity for mobility vehicles [Lee, 2019]. There are devices such as treadmills and escalators that assist with indoor mobility vehicles, but they are stationary installations that limit freedom of movement [Bianchessi et al., 2014]. Another mobility vehicle called "air-ride" is being used at Incheon Airport, but it also follows a predetermined course, reducing its usability.

There are examples of personal indoor mobility vehicles designed specifically for individual use, such as the Toyota 'Winglet'(Figure 1a), Honda 'U3-X'(Figure 1b) and the vehicle of [Bianchessi et al., 2014]. All three cases are personal electric vehicles without separate handles. Bianchessi [Bianchessi et al., 2014] highlights the importance of allowing the user to have a hands-free operation in situations where they need to perform tasks in an indoor environment. Additionally, the proposed product by Bianchessi addresses the usability limitations of self-balancing vehicles like the Honda U3-X and Toyota Winglet, where the driver needs to maintain balance. They achieve this by incorporating two additional caster wheels to ensure stability.

(a) Toyota 'Winglet M' (b) Honda U3-X

Figure 1: Examples of indoor personal mobility

(a) Initial concept sketch (b) First version of AngGo (c) Joystick included version

Figure 2: Concept development of AngGo

Including these factors, we have developed AngGo [Kang et al., 2020], an indoor shared mobility vehicle that can be ridden while seated. The recent version of AngGo is designed as a four-wheeled mobility vehicle with guaranteed balance and can be operated through a joystick or footplate control. Users can choose their preferred method of controlling the mobility vehicle, allowing them to use their feet for operation when they want to have hands-free control. Since the footplate control method is a newly proposed approach for personal mobility vehicle operation, it is less familiar to users compared to joysticks, and there is a lack of verification regarding the convenience and usability of this control method. AngGo has been developed and improved in various forms since 2019(Figure 2), and feedback is received through various usability evaluations and demonstrations. During demonstrations and evaluations, users provided feedback on footplate control, expressing fatigue and discomfort during driving. In order for the footplate operation to be used as an alternative to the joystick in line with the concept of AngGo, further research is needed to improve the convenience of the footplate control method.

1.2 Research aim

The purpose of this study is to propose methods to alleviate the physical burden during the operation of the sedentary mobility vehicle, AngGo, and validate them through experimentation. There are three main research questions for this study.

- What factors contribute to leg strain in the existing AngGo design?
- How can the footplate control system be redesigned based on the factors of the first research question?
- Does the revised design effectively reduce physical demand?

To answer the first research question, insights were gathered through interviews with a small-scale designer group, and we conducted some desk research and investigation to find the answer to the second research question. Based on the results, a new design was proposed. In accordance with the last research question, the process of validating whether the new design effectively alleviates physical demand was conducted through a comparative usability evaluation between the original design and the new design.

II Background: System of AngGo

2.1 Existing personal mobility and types of control

Various forms of personal mobility vehicles can be commonly seen, including e-scooters and electric kickboards. These mobility vehicles employ different control methods depending on their form and function. Referring to the book "Designing for People: An Introduction to Human Factors Engineering [Lee et al., 2017]," we classified existing mobility vehicles based on their control methods (Figure 3). The control methods can be divided into those using 1-dimensional track values and those using 2-dimensional track values depending on the directional control method. For example, kickboards or scooters typically use lever-based controls for 1-dimensional input to control speed, and physical steering to control the direction. Electric skateboards utilize a weight-shift structure for steering, requiring only a continuous slider-type controller for speed control. In contrast, when the steering is achieved using motors or by exploiting speed differences between the two wheels, 2-dimensional input is necessary. A prominent control method that utilizes 2D track values is the joystick. Conventional electric wheelchairs and seated-type personal mobility vehicles like WHILL [WHI,] employ joystick controls for speed and directional adjustments. Segway-type devices involve the use of the lower body or the entire body, primarily relying on weight-shift for speed control and using a tilting stick or the handle for steering. Two-wheeled electric boards utilize the tilt of both feet to control direction and input for forward and backward motion.

Figure 3: Categorization of existing PMVs' controller

2.2 Shared mobility service

Electric kick scooter sharing services can be easily found on the streets. These services effectively serve the purpose of last-mile mobility vehicles by providing mobility options without the need for dedicated rental stations or parking lots. Using GPS, the app displays the locations of nearby mobility vehicles as pins, allowing users to find and ride them. However, there are challenges such as fleet unbalance, where the mobility vehicles tend to accumulate in specific areas during certain situations or times. Additionally, once a mobility vehicle has been used and left at a location, it requires manual relocation to areas where the demand for mobility is higher. To address these issues, research from MIT [Lin, 2021] has proposed incorporating autonomous driving technology into personal mobility vehicles.

2.3 Shared indoor smart mobility, AngGo

AngGo [Kang et al., 2020] is a shared indoor smart mobility(SISM) that can be used as a transportation and a resting place in a large indoor space. In indoor environments, particularly in spaces such as airports or convention centers, fleet unbalance can become more pronounced. Due to limited space, it can be inconvenient to have shared kick scooters parked anywhere, potentially causing issues with indoor space utilization. To propose a shared mobility service tailored to indoor environments, we have also integrated autonomous driving technology. The autonomous driving feature of AngGo not only addresses fleet unbalance by repositioning mobility vehicles but also provides a taxi-like service that actively seeks potential users. Through autonomous driving, the mobility vehicle navigates indoors, identifying potential users. Users can summon the mobility vehicle to their desired location using the app. Once the usage is complete, the mobility vehicle moves to another location to address fleet unbalance or travels to charging and maintenance stations. For this purpose, AngGo needs to support both autonomous and manual driving.

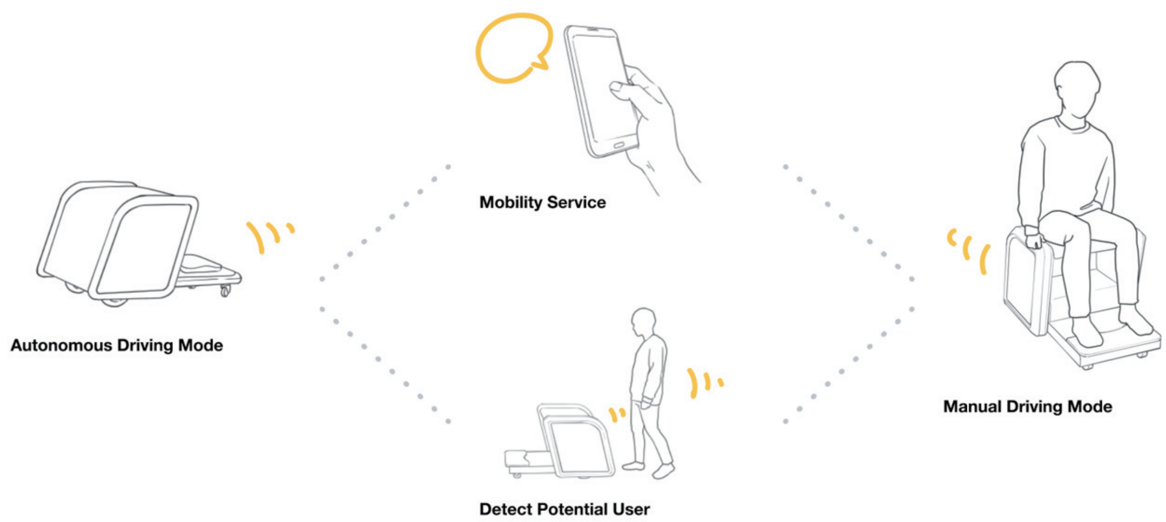


Figure 4: User scenario of SISM, AngGo

To enable autonomous driving for the mobility vehicle, it must have three or more wheels or be equipped with self-balancing capabilities to maintain stability. It should also allow for electric control of speed and direction, utilizing the 2D track values control method mentioned in Section 2.1. While a simple implementation could involve using a joystick, we propose a foot-operated control method to address the limitation of not being able to freely use both hands, which was found inconvenient in conventional personal mobility driving experiences. There are studies that have attempted to use foot-based input as a substitute for hands in various fields [Springer and Siebes, 1996, Carrozza et al., 2007]. The Segway-style method mentioned in Section 2.1 allows for hands-free operation, but self-balancing mobility vehicles may be challenging for some users to quickly grasp, and their stability may be lower compared to seated mobility vehicles such as WHILL or wheelchairs. To achieve a versatile and stable mobility design, AngGo is designed with a sedentary footplate steering method that enables the user to use both hands freely while maintaining stability during mobility boarding.

In large indoor spaces such as airports and convention centers, extensive walking distances often leave individuals longing for a place to sit and relax. Recognizing this need for both mobility and resting functionalities, we designed AngGo to serve as a versatile seating area resembling the shape of a chair. In the initial design, AngGo could be ridden by placing the feet on the footrest, and after stopping, it could be used as a chair-like resting area.

Subsequently, based on feedback received during the driving experiments, we incorporated features such as a backrest, armrests, and handholds to enhance stability. Additionally, considering user preferences, we ensured that both foot-operated and hand-operated driving options were available, allowing users to choose their preferred method. As a result, AngGo has evolved into its current form(Figure 2c), incorporating these improvements based on user feedback.

AngGo's system is divided into autonomous driving and manual driving. AngGo travels around the indoor space looking for potential users while driving autonomously, and at this time, it avoids obstacles through ToF cameras located in front and rear of AngGo. If the user expresses the boarding intention, the mobility vehicle stops, and when the user rides, manual driving using a footplate or joystick is possible.

Figure 5: First version of AngGo

Figure 6: Current version of AngGo

2.4 Footplate manipulation

The current footplate structure for manual driving is shown in Figure 7. This structure was implemented through two rails and IR distance sensors. It is designed to easily detect forward and backward and left and right rotation through IR sensors and rail structures in a way that controls the speed of each wheel by how far the footplate is from each sensor(Figure 8). The footplate maintains tension through the spring structure to return to the starting point.

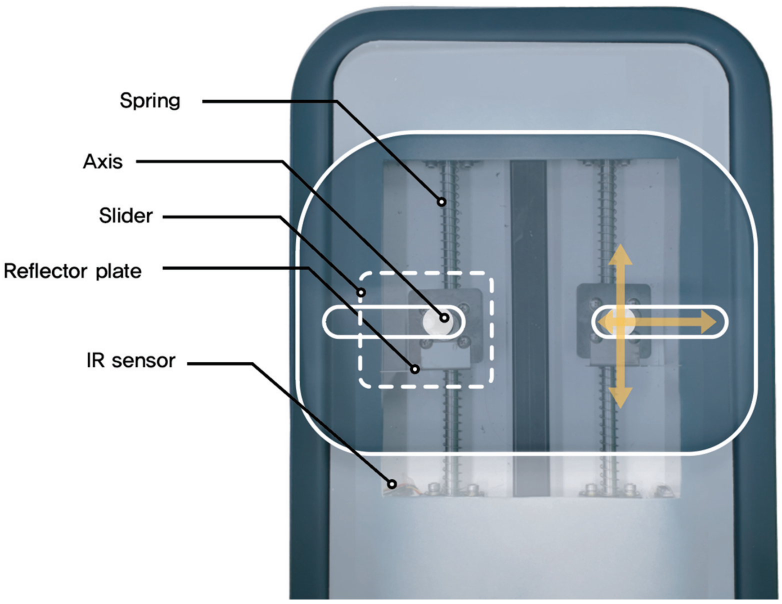


Figure 7: Structure of AngGo footplate

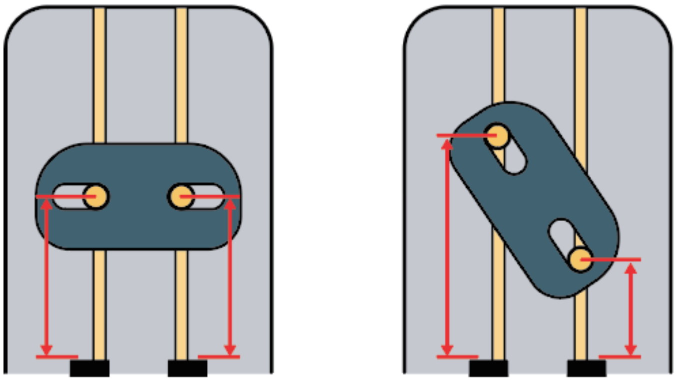


Figure 8: Mechanism of footplate sensing

2.5 Feedbacks of AngGo

AngGo recently participated in exhibitions and demos at CES2023, and is receiving feedback from users through demos in various places. Most users positively evaluate and enjoy the concept of the footplate manipulation, but they gave feedback that their legs are tired from using it for a long time and that it is hard to go backward. In addition, the insights from the observations show that rotation is required to some extent when reversing, but rotation in place is a function that should not be excluded because of the high frequency of use.

Figure 9: Demonstration in CES2023

Table 1: Feedbacks from demonstration

Feedback	Keyword
"It requires a lot of effort to reverse."	Reversing
"It would be great if there is a follow-me function that allows me to easily hop on the vehicle while walking."	Owning function
"It was challenging to perform precise directional control with the footplate."	Precise control
"I wish the joystick had a shorter response time."	Implementation
"I think my legs could get tired after prolonged use."	Physical demand
"It would be nice to have a lock feature that enables cruising without constant manipulation."	Physical demand, Cruising function

III Preliminary Study

Based on feedback from multiple demonstrations and experiments, we determined that it is necessary to reduce the physical demand during the operation of AngGo's sliding control mechanism in order to improve usability. To achieve this goal, we conducted a stage of identifying the factors that contribute to leg strain during manipulation. To explore foot-operated control examples and relevant research, we conducted desk research. We conducted practical experimentation with the existing sliding mechanism of AngGo and engaged in discussions with a designer group to identify the factors that contribute to leg fatigue. Based on these findings, we determined the direction for improvement.

3.1 Foot operated control

Before the ideation of foot-based control methods, we conducted desk research on relevant studies and examples of foot-based control. Research on foot-based control spans various fields such as foot-operated steering systems for individuals with disabilities, mobile and computer interfaces, and virtual reality interfaces. In the field of Human-Computer Interaction(HCI), there are cases where foot-based control methods have been analyzed and classified [Pearson and Weiser, 1986, Velloso et al., 2015]. By referring to the kinematic analysis of the joints in the leg, as described in these two papers, we can get insights into the typical and comfortable range of motion of the leg(Figure 10).

In the field of tangible interaction, there is research on foot-based interaction and gesture, which encompasses various types of feet interaction methods [Schmidt et al., 2014]. In this paper, they demonstrate foot-based tangible interaction methods where sliding or toggling motions are used to manipulate objects such as balls or cylinders. For a foot-operated steering system, it is necessary to control the speed and direction of the vehicle using the legs. Comparative studies on the usability of foot-operated steering vehicles have also been conducted [Song and Kim, 2017]. These vehicles involve using one foot for speed control using pedals, while the other foot is used for direction control. They can be divided into two main types: one that moves vertically, similar to bicycle pedals, and another that moves horizontally by rotating a disc(Figure 11).

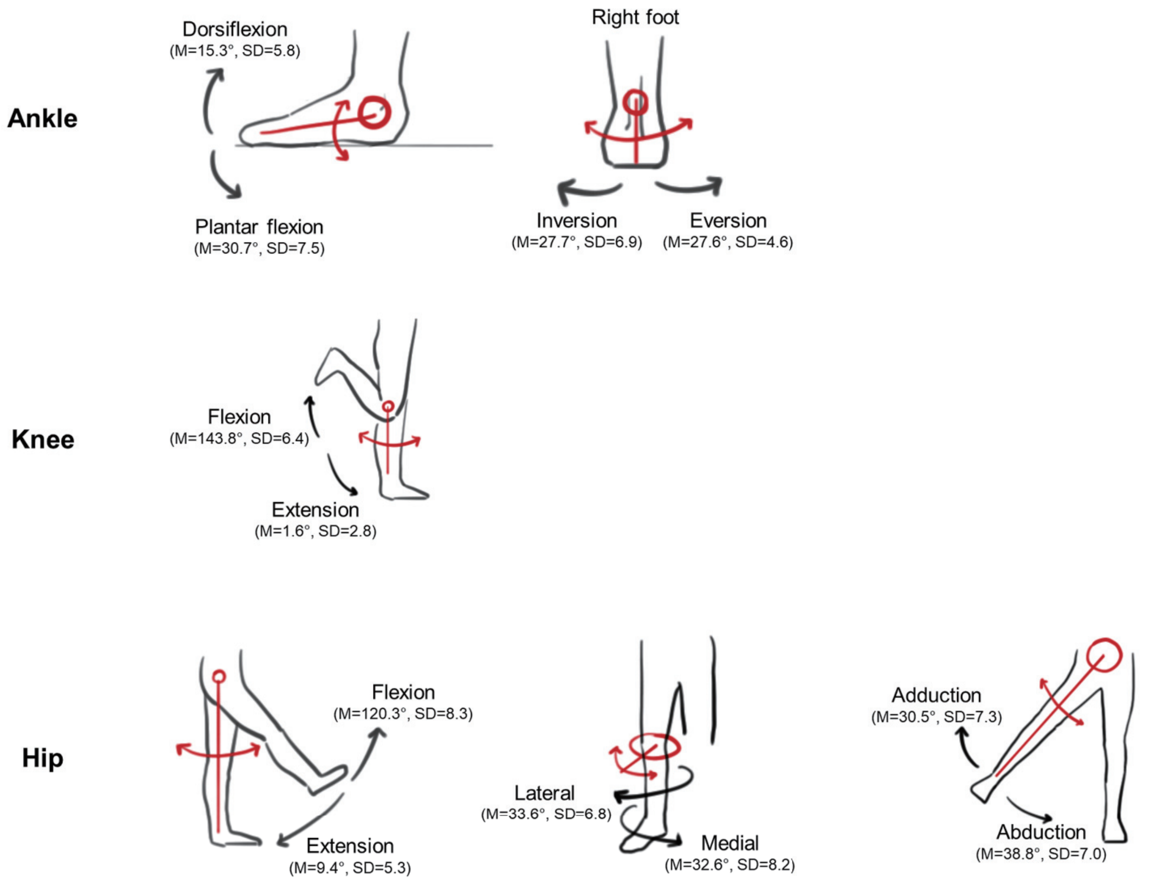


Figure 10: Normal range of motion of the right hip, knee, and ankle joints in male subjects, 30-40 years of age [Velloso et al., 2015] [Roaas and Andersson, 1982]

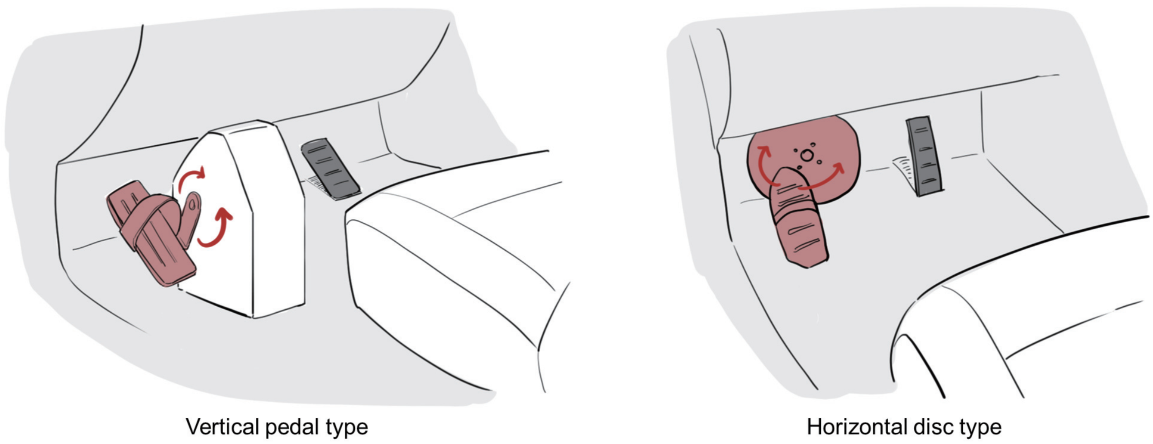


Figure 11: Methods of foot-operated steering vehicle

3.2 Test with prototype

The test and discussion were conducted with three design majors. The first session is to see the feeling of operation when driving, and when the user operates footplates, the mobility vehicle is manually moved according to the input to learn the feeling of operation, and a driving simulation was conducted. Participants boarded the AngGo and freely operated forward reverse left and right turns to perform the task of driving around the experimental space with obstacles. After the manipulation of each method was completed, participants filled out an evaluation questionnaire.
The second session was continuously entering each footplate for two minutes according to the instructions. After the completion of all sessions, we conducted short interviews with the participants to discuss the elements contributing to physical demand and the usability of the existing method. Through these interviews, we gathered insights and summarized the findings.

Figure 12: Prototype of sliding footplate

Table 2: Opinions and insights of preliminary study

Feedbacks	Insights
"It seems that in the existing seat height of AngGo, the footplate is positioned further away compared to its current location, and it would be more comfortable if the foot could be stretched further to reach the footplate."	Specification effects demand
"The angle and shape of the footplate have a large effect on reducing fatigue."	Incline degree effects demand
"Since forward driving is common, it is important to minimize fatigue during such situations."	Focusing driving scenario
"The sliding mechanism provided effective physical feedback."	Importance of physical feedback

3.3 Insights and findings

Based on the insights gathered from the interviews, the summarized findings are presented in the Table 2.

Among the feedback received through the interview, the proportion of situations that go straight in the actual use scenario is large, so it should be designed to make more effortless operation when going straight, and it is less difficult to go backward by putting a footplate on the heel than to put strength on the toe. Additionally, referring to car seats as an example, a participant mentioned that a slightly extended leg position, rather than a right-angle position, could provide a more comfortable posture.

Therefore, there are two factors to consider for improving the footrest:

- Seat and footplate positioning for the comfortable leg angle of the rider.
- Footplate design modification to facilitate reversing based on human factor engineering.

By addressing these factors, we aim to enhance the user experience and reduce demand during driving.

IV Design

4.1 Location and size

Based on the experimental results, investigations were conducted to revise the initial position and angle to reduce fatigue. As there were no previously researched cases specifically addressing posture in a seated position for angled foot control in AngGo, which differs in purpose from conventional chairs and vehicle seats, the comfortable seat height and leg angles may differ from those of typical chairs or vehicle seats. Therefore, a investigation was conducted to measure applicable specifications for AngGo, focusing on the comfortable saddle height and leg angles, targeting adult males and females without lower limb disabilities. Participants were asked to provide their preferred seat height (H) and footplate distance (L) for comfort. H represents the height from the sole of the foot to the seat, and L represents the distance from the back of the heel to the backrest. The criteria for comfort were based on the boarding and foot movement actions.

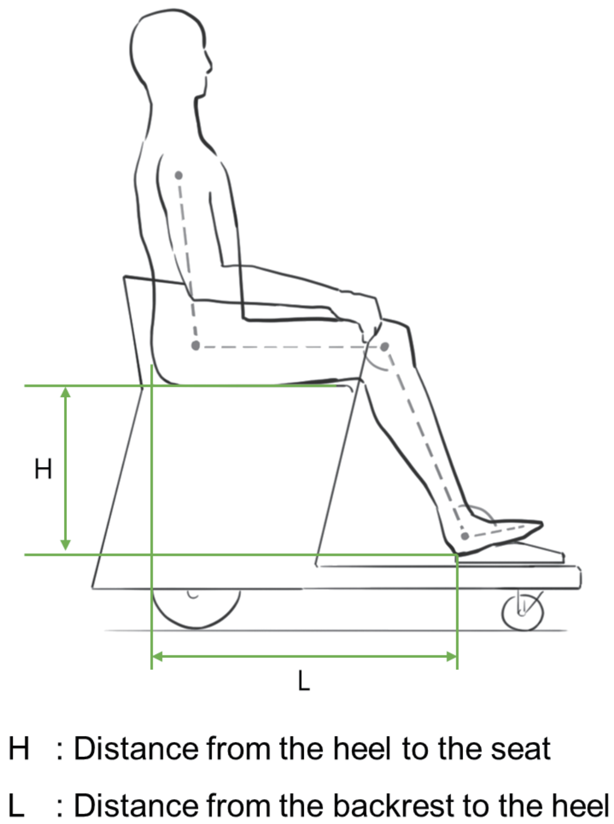


Figure 13: Description of H and L

Table 3: Height distribution of 30 participants

	Male	Female
Height	163cm 170cm 180cm 186cm 173cm 164cm 178cm 169cm 171cm 178cm 178cm 164cm 183cm 172cm	167cm 162cm 166cm 163cm 167cm 165cm 160cm 163cm 159cm 160cm 162cm 159cm 165cm 167.5cm 160cm 160cm
# of participants	14	16
Mean	173.5	162.8

Investigation : participants

The investigation was conducted with a total of 30 Korean participants in their 20s to 30s, consisting of 14 males and 16 females. H represents the height from the heel to the seat surface, and L indicates the distance from the backrest to the heel. Since the leg position is not freely adjustable like a typical chair and assumes a sliding operation method, a sliding distance of 12 cm was assumed. The most comfortable position and the minimum and maximum values within the comfortable range were investigated. The information regarding the height and gender of the 30 participants involved in the investigation is presented in the following table3.

Investigation : results

According to the experimental results, since the number of participants investigated was over 30, it can be assumed that they follow a normal distribution. The participants' heights ranged from a minimum of 159cm to a maximum of 186cm and the average of their height is 167.8cm. The average comfortable seat height from the footrest was 40.56cm, with a standard deviation of 3.997. The average comfortable footrest distance for the origin was 59.37cm, with a standard deviation of 6.585. The average of the minimum comfortable value was 48.5cm (SD=7.813), and the average of the maximum comfortable value was 66.2cm (SD=4.483). Assuming a total movement range of 12cm, with 6cm forward and 6cm backward as in the existing system, if the footplate distance is 59cm, it can be concluded that the movement falls within the range of the minimum and maximum comfortable values, indicating that it is within the comfortable range. Furthermore, referring to the investigated range of minimum and maximum comfortable values, it would be useful to consider adjusting the range of footplate movement for hardware improvements or usability improvements. These findings represent data obtained from participants in Asia, specifically South Korea.

Based on the investigation, the height H of the seat to be applied to AngGo was determined to be the average value of 40.5cm, and the distance L of the footplate was determined to be the average value of 59cm.

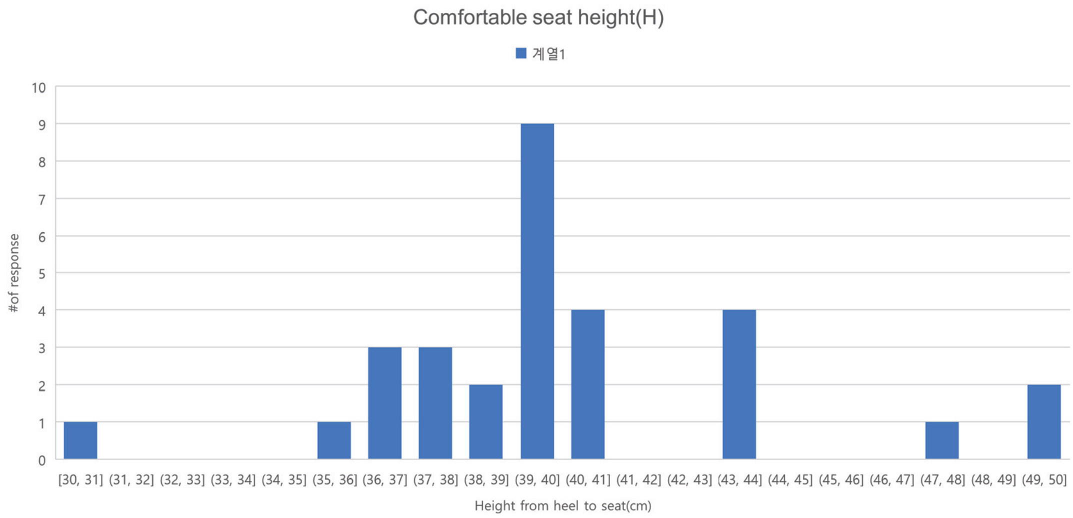


Figure 14: Result of comfortable height(H)

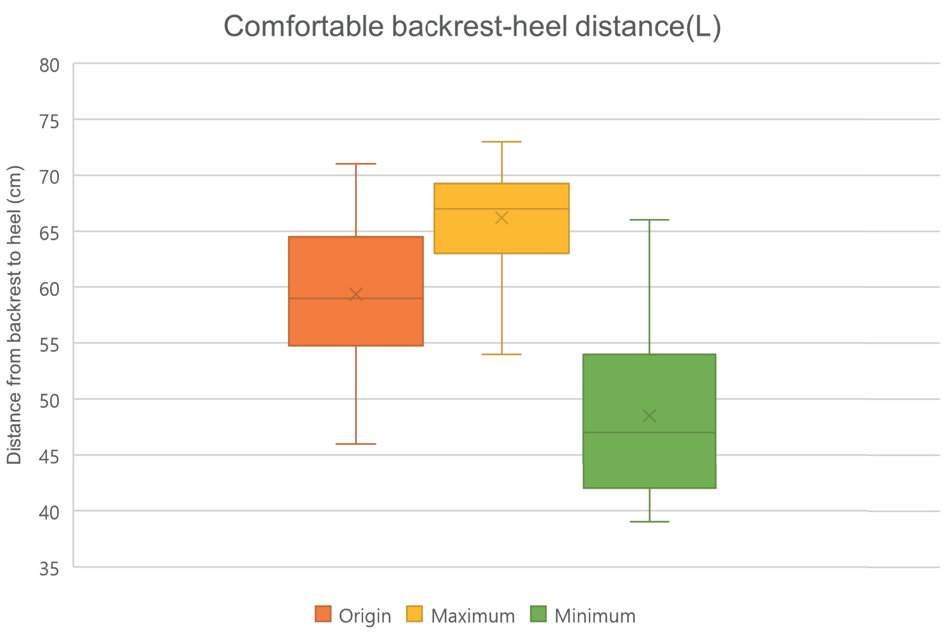


Figure 15: Results of comfortable distance(L)

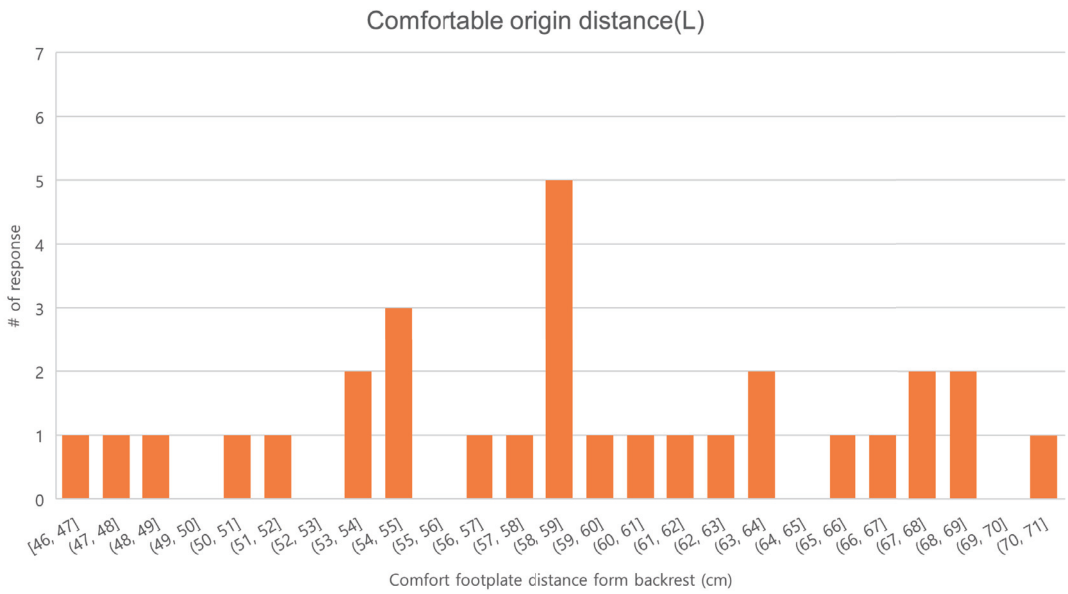


Figure 16: Result of comfortable origin distance(L)

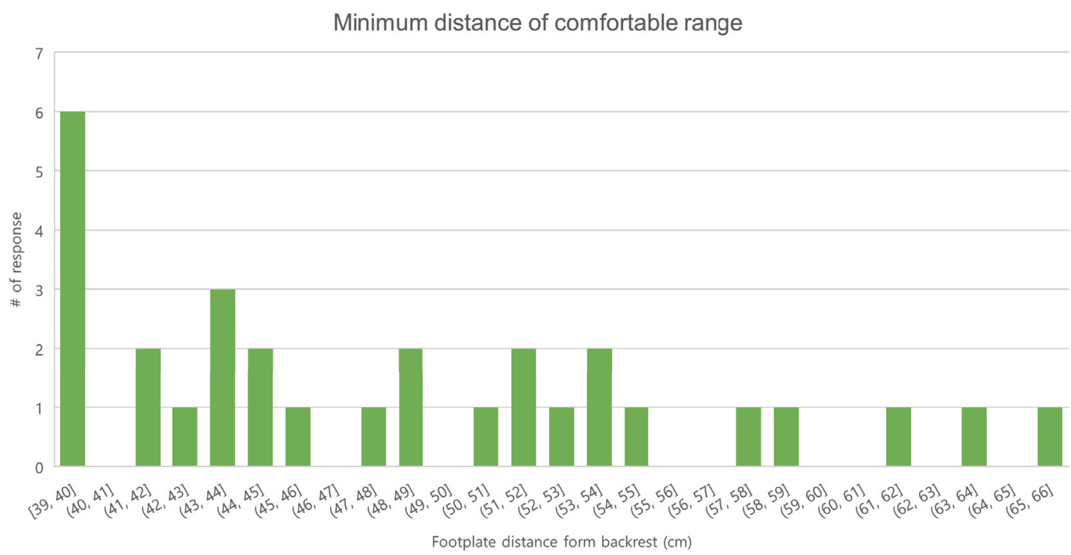


Figure 17: Result of comfortable maximum distance(L)

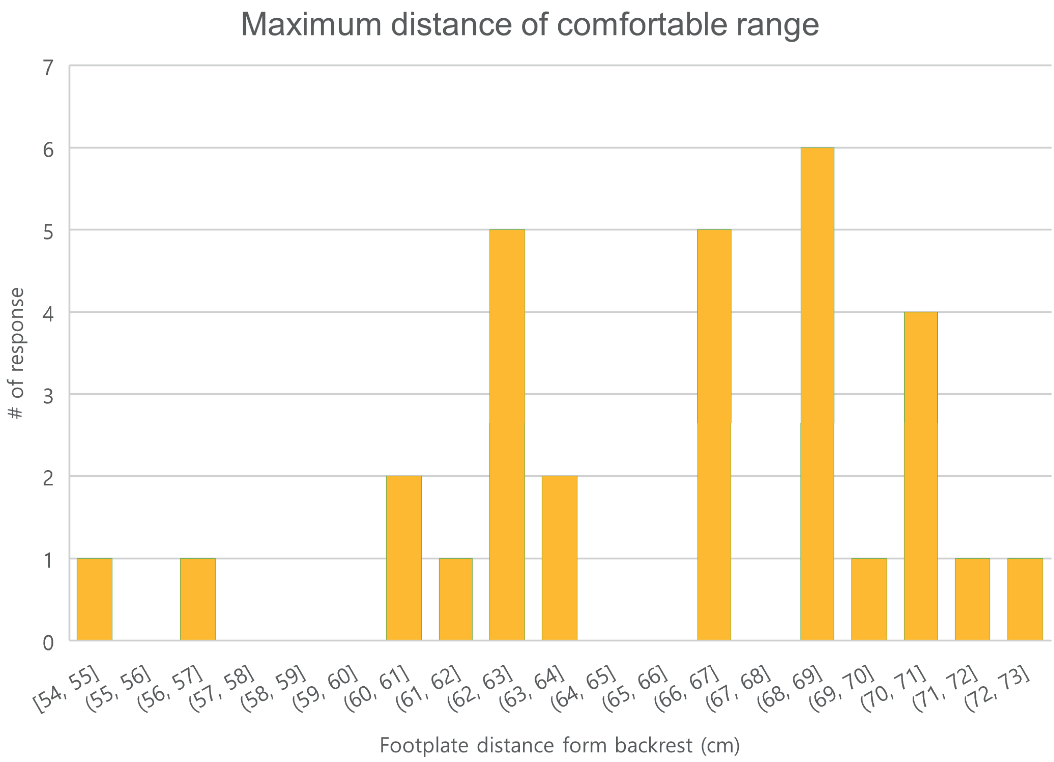


Figure 18: Result of comfortable minimum distance(L)

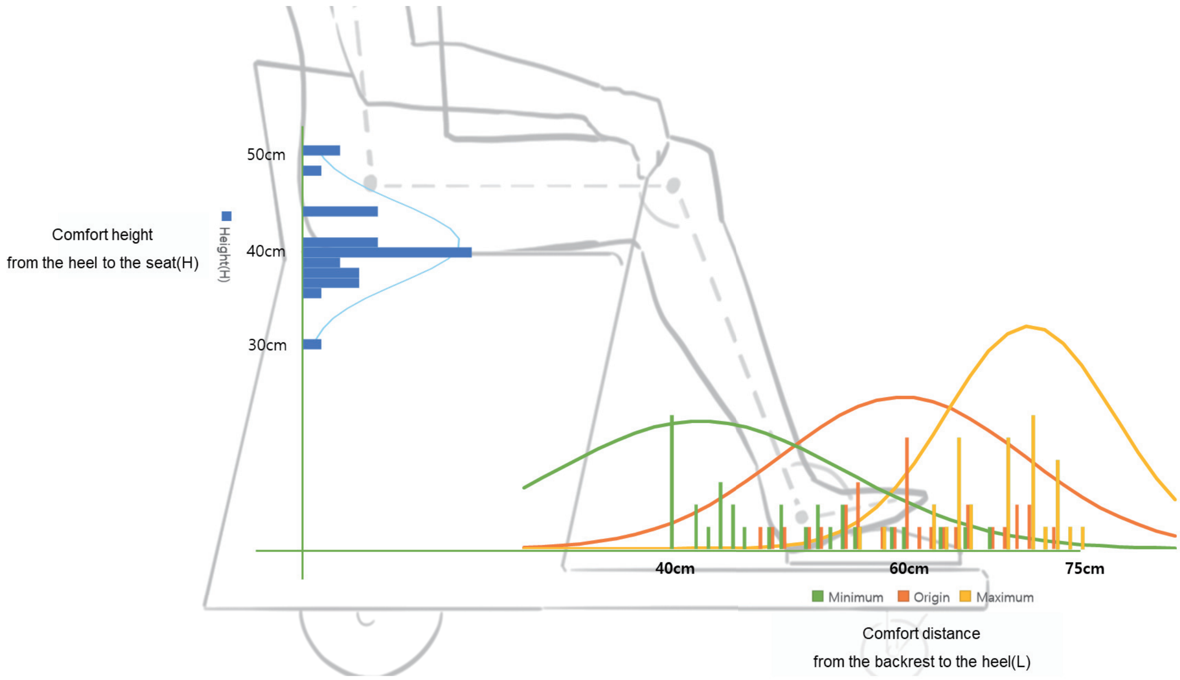


Figure 19: Summary of comfortable H-L result

Incline degree of footplate

Referring to the result of the investigation conducted by Size Korea, the average knee height and hip-to-knee distance of individuals in their 20s, the range of motion for the sliding footplate of the improved seated-type mobility vehicle is as follows(Figure 20).

$$tan^{-1}(\frac{73.5mm}{455mm}) = 9.09^{\circ}$$
$$tan^{-1}(\frac{13.5mm}{455mm}) = 1.72^{\circ}$$
$$tan^{-1}(\frac{133.5mm}{455mm}) = 16.27^{\circ}$$

The range of motion for the knee is 1.72 to 16.27 degrees. Based on the insight obtained from the previous chapter, where the proportion of forward and stop actions is significant in the driving scenario, it was deemed necessary to design a footplate that facilitates forward motion. The previous design of AngGo's footplate had a half-and-half incline to assist both forward and backward movements(see Figure21). However, this design lacked a rationale for the incline degree of the footplate, so the further improvement was sought by referring to literature on comfortable ankle angles.

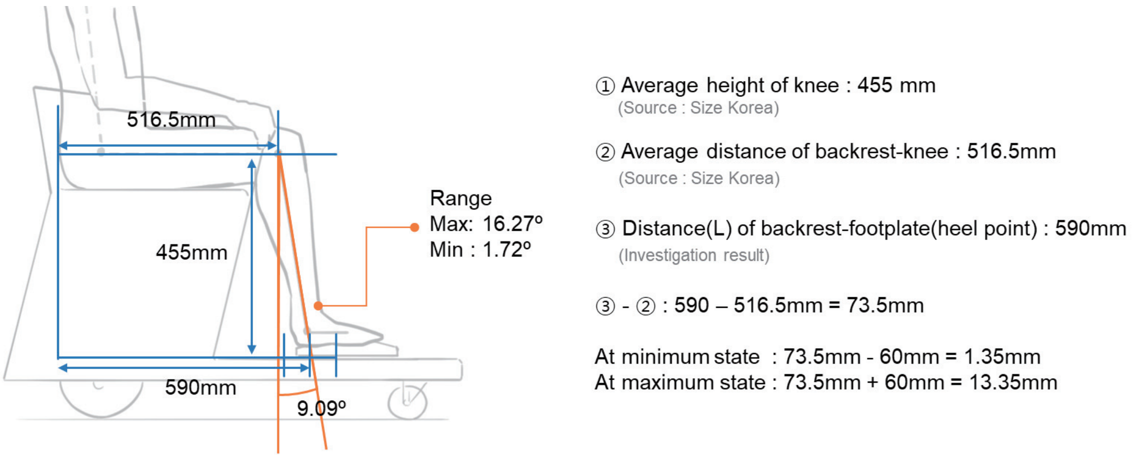


Figure 20: Range of joint in revised specification

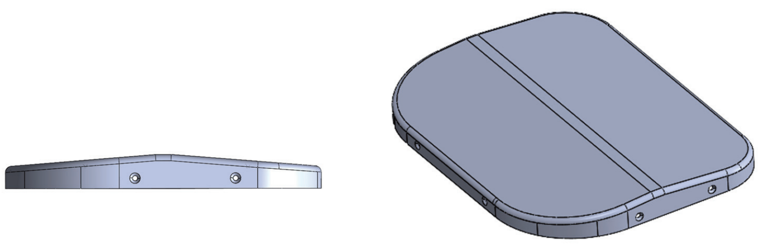
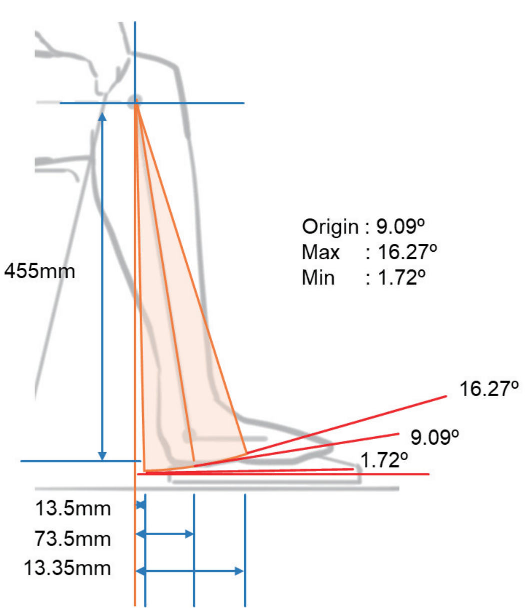
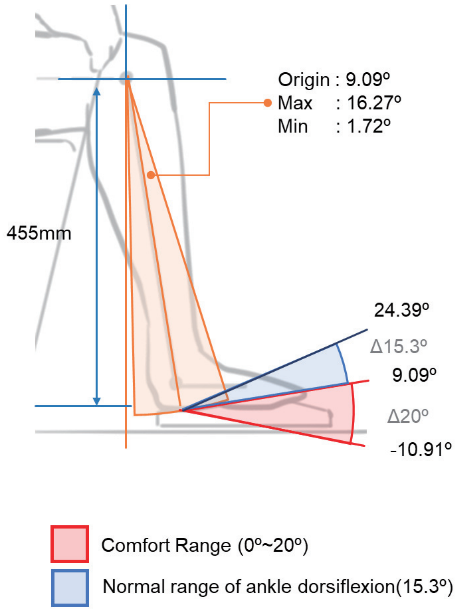


Figure 21: Previous design of footplate

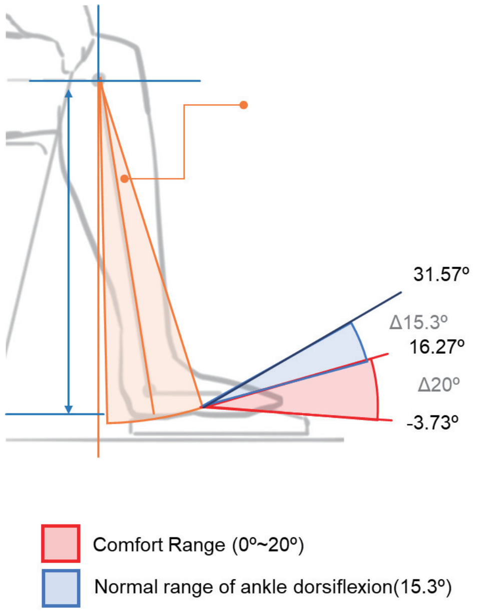
Generally, ankle angles of 90 to 110 degrees are perceived as comfortable [Park et al., 2000, Kyung and Nussbaum, 2009]. Additionally, the dorsiflexion range of the ankle is approximately 15 degrees(15.3 degrees) on average [Roaas and Andersson, 1982].



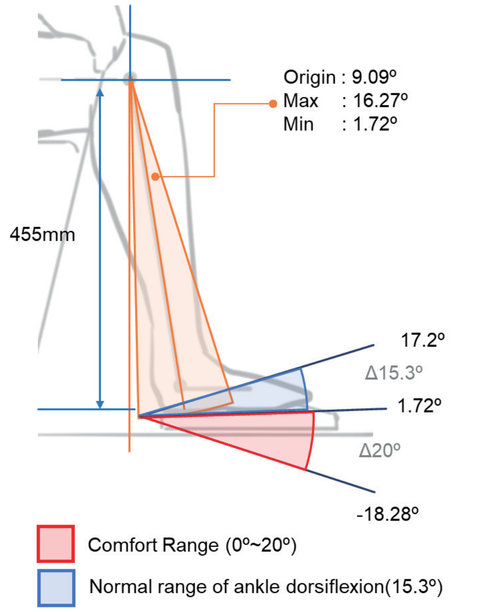
(a) The angles when the legs and feet are perpendicular



(b) Ankle range at the origin position



(c) Ankle range at the maximum position



(d) Ankle range at the minimum position

Figure 22: Comfort ankle range for design footplate

Based on the improved specifications of the sliding mechanism, the footplate angle should not exceed 31.57 degrees when pushed to the maximum, and a comfortable range is 16.27 degrees to -3.73 degrees(Figure 22c). The footplate angle should not exceed 17.2 degrees when pulled to the minimum, and a comfortable range is 1.72 degrees to -18.28 degrees(Figure 22d). Thus, based on these values and considering the forward and stop states, the desirable footplate angles range from 9.09 to 16.27 degrees(it should not exceed 17.2 degrees). A footplate angle of 13 degrees was set for the experiment. The final specifications of AngGo are depicted in the following image(Figure23).

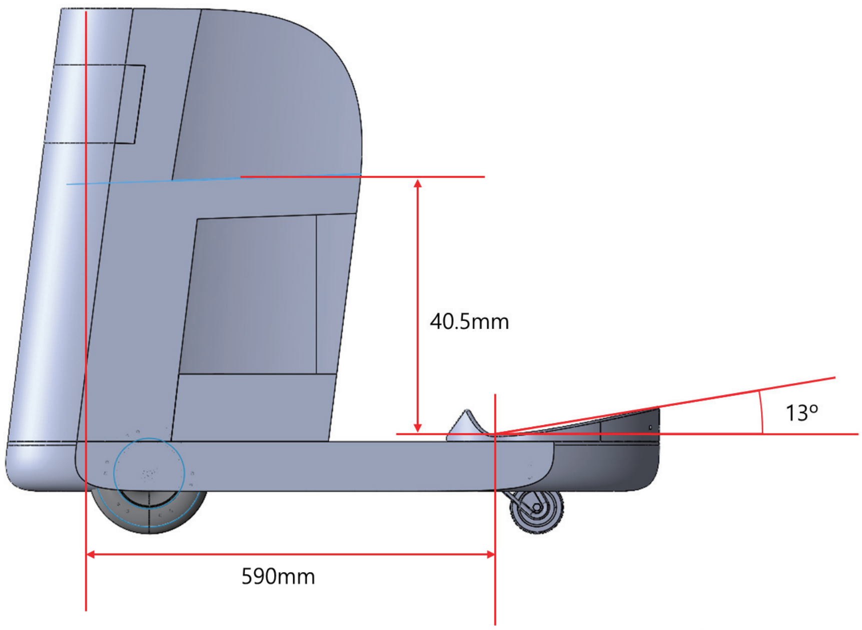
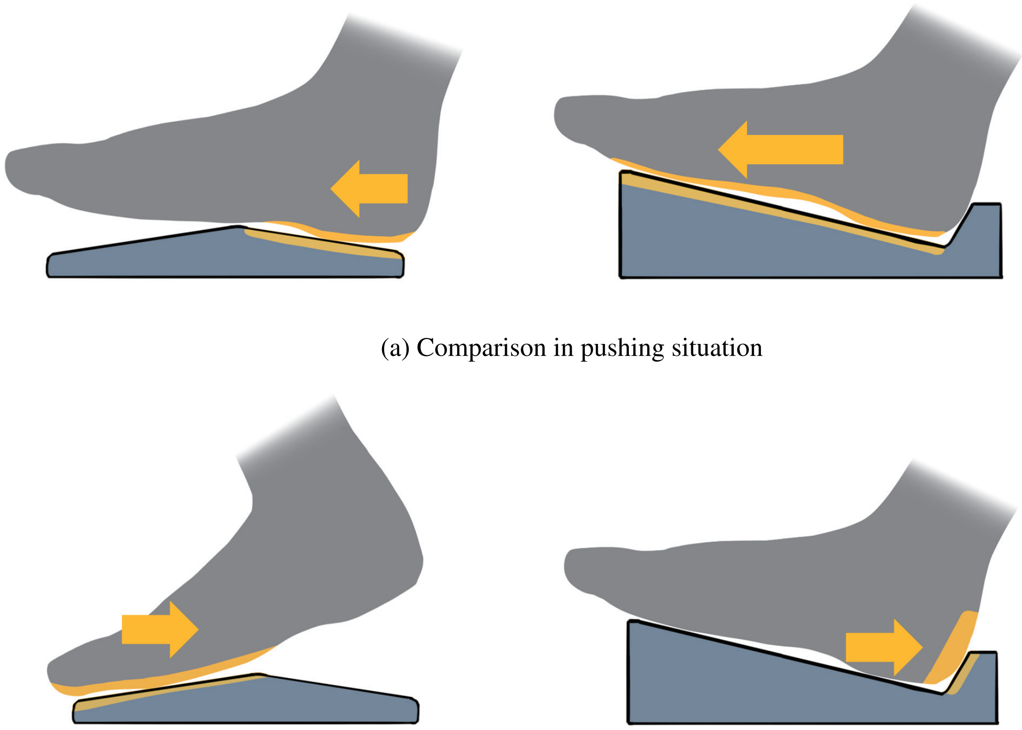


Figure 23: Revised specification of AngGo



(a) Comparison in pushing situation

(b) Comparison in pulling situation

Figure 24: Anthropometric comparison of existing form(left) and suggesting form(right) of footplate

4.2 Redesign footplate and structure

Based on the aforementioned specifications, we proceeded with the design of the footplate and internal structure that would complement the current design of AngGo.

As shown in Figure 24, in the sliding motion of the foot on the footplate, the existing footplate design has a small slope, relying on friction for effective movement. In contrast, the proposed footplate design introduces an overall slope to facilitate better force transmission in the pushing direction. The previous design of the footplate featured a tilted structure that facilitated pulling by using the toes for backward movement. However, in the insight section, the opinion was received that exerting force on the front of the foot may further contribute to fatigue in the legs. In response, a modification to the design was proposed, incorporating a structure where the footplate engages the heel, allowing for pulling. Based on the previously conducted surveys on ankle angles, various sketches were created by introducing an overall tilt to the footplate and incorporating a structure that engages the heel of the foot.

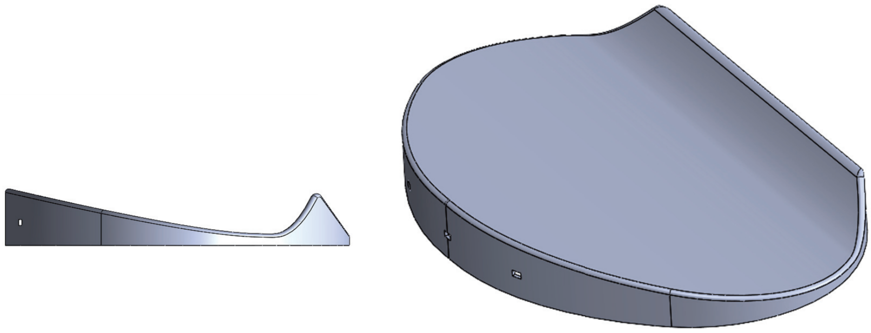


Figure 25: Revised design of footplate

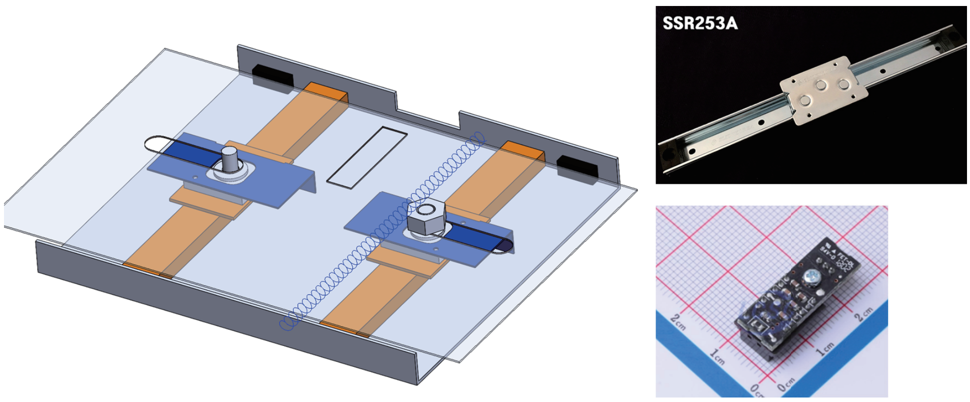


Figure 26: New structure and components

Among various sketches, we applied a developed form that harmonized with AngGo's design and conducted modeling(Figure28). Additionally, we simplified and downsized the existing footplate structure to make it more suitable for the new AngGo. The original rail structure utilized a unit and abrasive rod, which increased the height of the footplate structure due to the space between the abrasive rod and the floor. To lower the height and simplify the structure while widening the design scope, we employed LM guide types instead of cylindrical shafts and units.

In contrast to the existing footplate's internal structure, which requires a height of approximately 5cm, the newly designed internal structure using the new components can perform the necessary functions within a height of around 2.5cm. As a result, it enables a thinner design of the footplate and the area beneath it, allowing for more diverse forms to be explored.

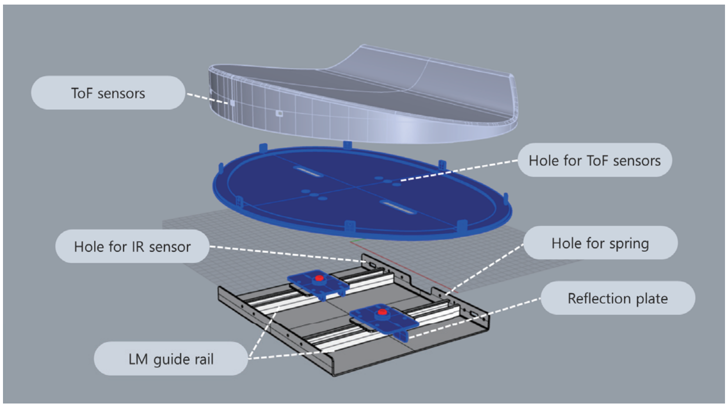


Figure 27: Final design of footplate structure

Figure 28: Comparison of revised footplate

V Usability Evaluation

Based on the experimental results conducted in the Design chapter, we applied adjustments to the seat height, footplate distance, and footplate angle in order to incorporate them into a functional AngGo prototype. Subsequently, a usability evaluation was conducted to compare the original specification AngGo with the improved specification AngGo. The evaluation utilized the NASA TLX scale [Hart and Staveland, 1988] to measure workload.

5.1 Participants

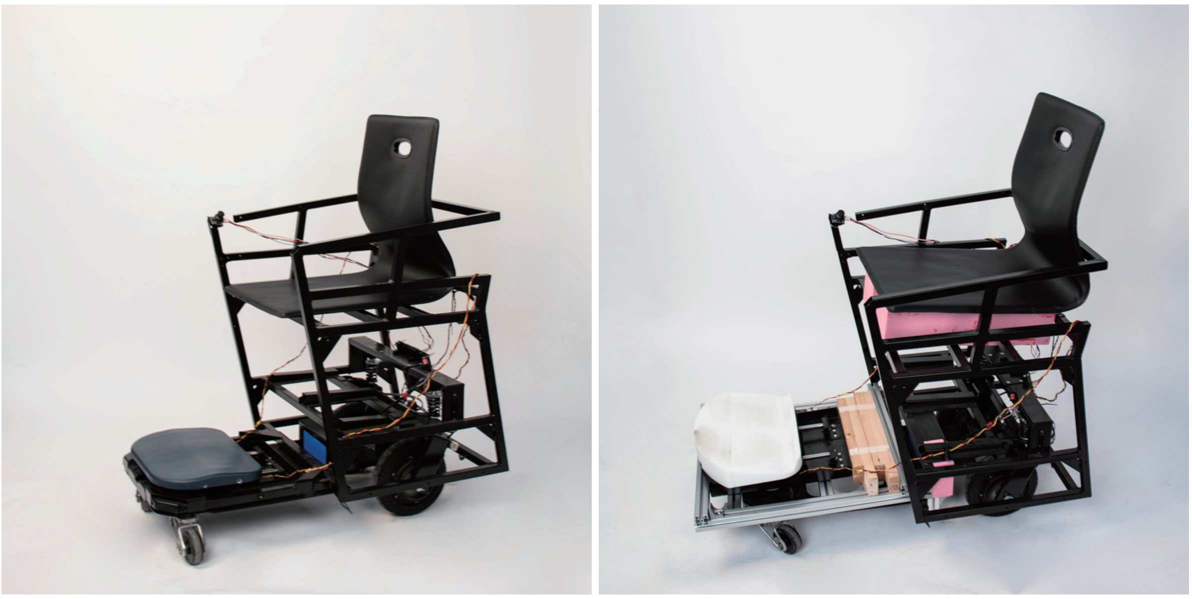
A total of 20 participants (12 males, 8 females) were recruited for the experiment. The participants were individuals without any leg disabilities in their 20s to 30s. Their demographic information is presented in table 4. According to Nielsen's paper [Nielsen and Landauer, 1993], a group size of 15 or more is considered sufficient to identify usability problems. Among the participants, 60% were male and 40% were female. The height of the participants ranged from a minimum of 159 cm to a maximum of 186 cm. In terms of driver's license possession, 60% of the participants had a license, while 40% did not. Regarding previous experience with personal mobility vehicles such as electric scooters and Segways, 35% were inexperienced, 35% had ridden them 1-2 times, and 30% were frequent riders. Prior to the experiment, the participants were provided with instructions on the footplate control method of AngGo and underwent a practice session to familiarize themselves with the operation. Participants received a compensation of 20,000 KRW for their participation in the experiment.

Table 4: Demography of participants

Participants	Gender	Height	Experience of PMVs	Driver license
P1	Male	172	A few times	Y
P2	Male	178	None	N
P3	Male	186	A few times	Y
P4	Female	163	None	N
P5	Female	159	A few times	Y
P6	Female	162	None	N
P7	Female	163	A number of experience	Y
P8	Male	173	A few times	Y
P9	Male	171	A number of experience	Y
P10	Male	183	A number of experience	Y
P11	Male	164	None	Y
P12	Female	160	None	N
P13	Male	178	A number of experience	N
P14	Female	170	None	N
P15	Male	178	A number of experience	Y
P16	Male	174	A few times	Y
P17	Male	169	A number of experience	Y
P18	Male	180	A few times	N
P19	Female	168	None	N
P20	Female	167	A few times	Y

5.2 Method

The experiment was conducted using a working prototype, and during the participant's completion of the given tasks, observations were made to record the occurrences of issues such as sudden acceleration, sudden braking, and collisions, as well as the task completion time. After the completion of the driving session, the participants filled out a workload questionnaire. A brief interview was conducted to collect feedback after two rounds of experiments. The workload assessment questionnaire utilized the NASA Task Load Index (TLX) scale, which consisted of six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration.



(a) Testbed of existing design

(b) Testbed of revised design

Figure 29: Working prototypes for usability test

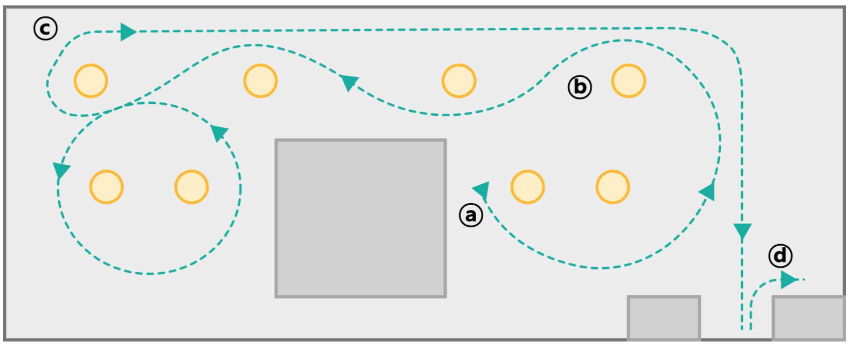


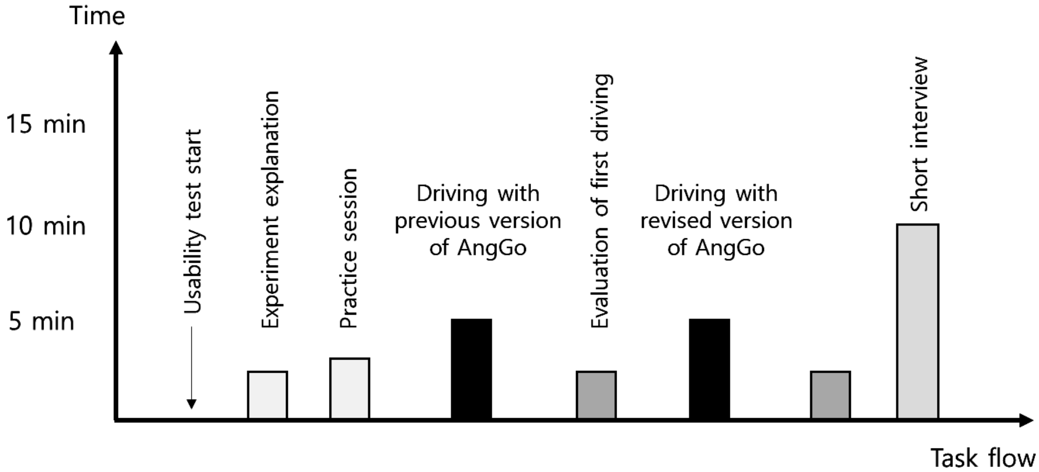
Figure 30: The pathway of the driving test, (a)big curve (b)S-curve (c)straight (d)backwards driving

5.3 Experiment process

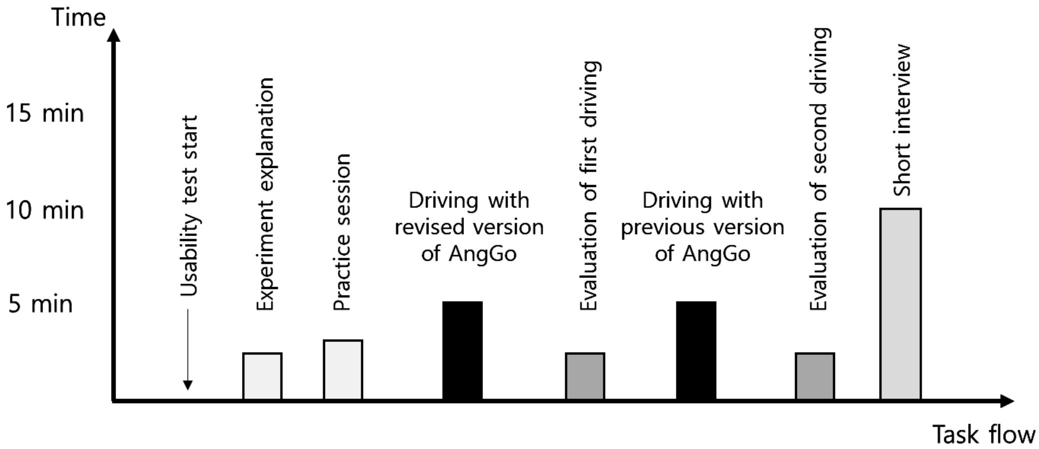
The usability evaluation was conducted following the flow:

- The experimenter provided an explanation of the purpose of the experiment and gave instructions on how to operate prototypes.
- Users sat on the testbed and were given enough time to practice and familiarize themselves with the operation methods. The practice session was conducted on the testbed they would use for the first session, depending on the participant group.
- The experimenter explained the items on the workload measurement questionnaire(NASA TLX), and participants proceeded with the experiment while being aware of each item.
- For Group A, the driving session was conducted using the original AngGo frame. The driving pathway was as shown in the figure30 and included tasks such as forward driving, left and right turns, and reverse driving. The driving session lasted for 5 minutes. An observer recorded the completion time of tasks and the number of issues encountered.
- After the driving session, participants completed the NASA TLX questionnaire.
- Using the revised AngGo testbed, another driving session of 5 minutes was conducted. The driving course and observer's tasks were the same as in the previous driving session.
- After the driving session, participants completed the NASA TLX questionnaire.
- Once all sessions were completed, a short interview was conducted to gather feedback.

Figure 31: Driving task in the usability test



(a) Usability test process of Group A



(b) Usability test process of Group B

Figure 32: The process of usability test

VI Result

We collected task completion time, scores on the 6 scales of NASA TLX, and interview results through the experiment. During the experiment, there were instances where the prototype experienced issues during the reverse maneuver, resulting in significantly increased task completion time for two participants (P6, P13). Among the participants who encountered issues during the experiment, one participant belonged to Group A and the other belonged to Group B. It is presumed that these prototype operational issues may have influenced the scores on the NASA TLX scales. Indeed, the Performance and Frustration data of the two participants exhibited notable differences that could be considered outliers. Therefore, we treated these two data points as invalid and analyzed the results of the remaining 18 participants.

6.1 Work load scale

The analysis of the experimental results was conducted using paired t-tests for each item of NASA TLX. Since the sample size of participants was n=18, which is less than 30, the Shapiro-Wilk test, suitable for data with a small sample size, was performed for testing normality. Additionally, the homogeneity of variances was assessed using One-way ANOVA. The 1st data for each item represents the results of the session conducted on the testbed using the previous specifications of AngGo, while the 2nd data corresponds to the results of the session conducted on the testbed using the improved specifications of AngGo. For example, Mental1 data indicates the Mental demand results from the testbed session using the previous AngGo specifications, while Mental2 data represents the Mental demand results from the testbed session using the improved AngGo specifications.

Normality test

When calculating with an alpha value of 0.05 for a confidence level of 95%, in the case of Mental demand, the p-value for Mental1 data is 0.021, which is less than 0.05, indicating that it does not exhibit a normal distribution. On the other hand, for Mental2 data, the p-value is 0.202, which is greater than 0.05, suggesting that the data is normally distributed. Therefore, the analysis of Mental demand will be conducted using non-parametric tests. The p-values for Physical1 and Physical2 data are 0.201 and 0.372, respectively, indicating that both variables have p-values greater than 0.05. Therefore, it can be concluded that these variables follow a normal distribution. The p-value for Temporal1 data is 0.406, and for Temporal2 data, it is 0.804, both of which are greater than 0.05. Hence, it can be inferred that the temporal data also exhibit normality.

Table 5: Normality test(Shapiro-Wilks test) results of Mental, Physical and Temporal demand

	Mental1	Mental2	Physical1	Physical2	Temporal1	Temporal2
p-value	0.021	0.202	0. 201	0.372	0.406	0.804
Average	10	7.61	12.89	7.89	8.94	7.167
Median	13	6	12.5	7.5	8.5	7.5
Standard Deviation(SD)	5.6672	5.3041	3.9391	4.3641	4.4652	4.5665
Normality	p-value<α, reject the H0.	p-value > α, accept the H0.	p-value > α, accept the H0.	p-value > α, accept the H0.	p-value > α, accept the H0.	p-value > α, accept the H0.

Table 6: Normality test(Shapiro-Wilks test) results of Performance, Effort, Frustration

	Performance1	Performance2	Effort1	Effort2	Frustration1	Frustration2
p-value	0.005838	0.000395	0.3476	0.02727	0.4555	0.3958
Average	6.33	5.3889	8.7222	6.722	9.889	7.833
Median	5	4	8	5	9.5	7
Standard Deviation(SD)	4.1302	4.5132	4.2951	4.5479	4.0277	5.0205
Normality	p-value<α, reject the H0.	p-value<α, reject the H0.	p-value > α, accept the H0.	p-value<α, reject the H0.	p-value > α, accept the H0.	p-value > α, accept the H0.

The p-values for Performance1 and Performance2 are 0.005838 and 0.000395, respectively, indicating that both values are less than 0.05. Therefore, the data for Performance does not exhibit normal distribution, and a non-parametric test will be conducted. The p-value for Effort1 is 0.3476, and the p-value for Effort2 is 0.02727, indicating that Effort2 data does not exhibit a normal distribution. Therefore, a non-parametric test will be conducted. The p-values for Frustration1 and Frustration2 are 0.4555 and 0.3958, respectively. The p-value for Frustration is greater than 0.05, suggesting that it can be considered normally distributed.

Table 7: Results of homogeneity of variances test(One-Way ANOVA)

	Mental demand	Physical demand	Temporal demand	Performance	Effort	Frustration
p-value	0.4193	0.8733	1	0.8937	0.8962	0.3
Average of |data-mean|	1 : 5.11 2 : 4.45	1 : 3.44 2 : 3.56	1 : 3.61 2 : 3.61	1 : 2.99 2 : 3.12	1 : 3.58 2 : 3.47	1 : 3.33 2 : 4.16
SD of |data-mean|	1 : 2.11 2 : 2.67	1 : 1.72 2 : 2.38	1 : 2.48 2 : 2.65	1 : 2.757 2 : 3.17	1 : 2.21 2 : 2.82	1 :2.11 2 :2.61

Homogeneity of variances test

The test for homogeneity of variances can be determined by conducting a One-Way ANOVA test on the modified data, which is obtained by subtracting the mean from each data point. If the resulting p-value is greater than 0.05, it indicates that the assumption of homogeneity of variances holds. The mean, variance, and p-value for the absolute differences between the data and the mean for each category are shown in the table. For Mental Demand, the p-value is 0.9339, which is greater than the critical value (alpha = 0.05). The p-value for Physical Demand is 0.1894, exceeding 0.05. The p-value for Temporal Demand is 0.8164, while for Performance, Effort, and Frustration, the p-values are 0.5555, 0.9262, and 0.0627, respectively. All p-values for these variables exceed the threshold of 0.05, indicating that homogeneity of variances is upheld for each category. Therefore, based on the results of the previously conducted normality tests, non-parametric tests and paired t-tests are performed separately.

Paired t-test and Wilcoxon signed-ranks test

For Mental demand, Effort, and Performance, although they satisfy the assumption of homogeneity of variances, they do not exhibit normality. Therefore, the significance of the results will be assessed using the non-parametric Wilcoxon signed-ranks test. As for the remaining variables, Physical Demand, Temporal Demand, and Frustration, since they satisfy both the normality and homogeneity of variances tests, the significance of the results will be determined using paired t-tests.

For Mental Demand, results of the Wilcoxon Signed-Rank test indicated that there is a non-significant large difference between Before (Mdn = 13 ,n = 18) and After (Mdn = 6 ,n = 18), Z = -1.9, p = .060, r = -0.6. Physical Demand was analyzed using a paired t-test, and the result of the paired-t test indicated that there is a significantly large difference between Before (M = 12.9, SD = 3.9) and After (M = 7.9, SD = 4.4), t(17) = 5.2, p < .001.

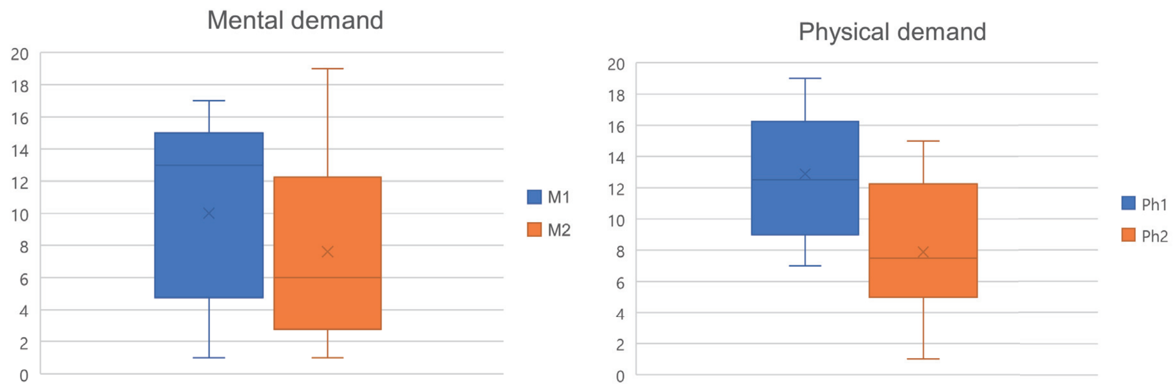


Figure 33: NASA TLX result of mental demand and physical demand

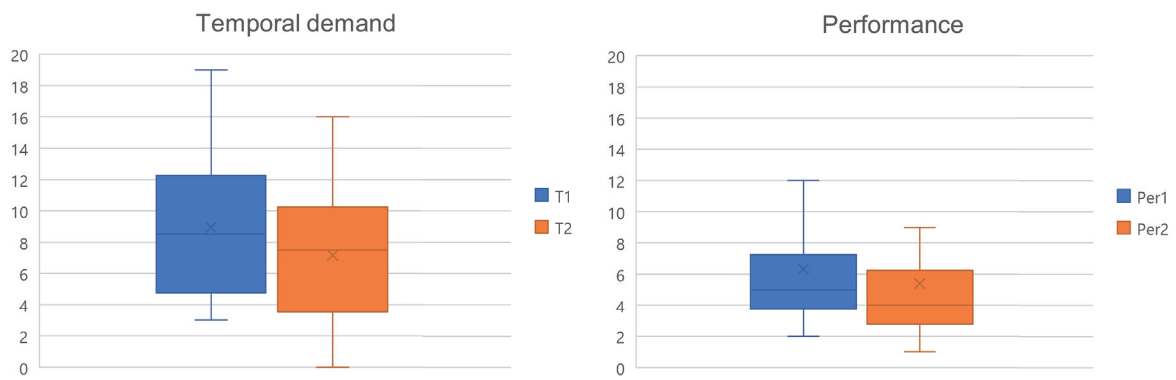


Figure 34: NASA TLX result of temporal demand and performance

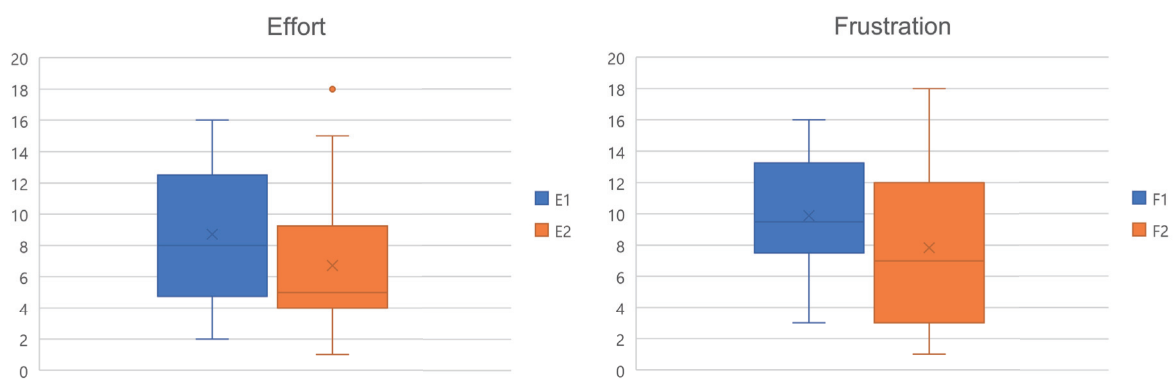


Figure 35: NASA TLX result of effort and frustration

Regarding Temporal Demand, the result of the paired-t test indicated that there is a non-significant small difference between Before (M = 8.9, SD = 4.5) and After (M = 7.2, SD = 4.6), t(17) = 1.9, p = .077. Since Performance does not meet the assumption of normality, the non-parametric Wilcoxon signed-ranks test was conducted, yielding a p-value of 0.281, which is greater than 0.05. Therefore, there is a non-significant small difference between Before (Mdn = 5, n = 18) and After (Mdn = 4, n = 18), Z = -1.1, p = .281, r = -0.3.

Data of Effort does not meet the assumption of normality, the non-parametric Wilcoxon signed-ranks test was conducted. The result of the Wilcoxon Signed-Rank test indicated that there is a significantly large difference between Before (Mdn = 8, n = 18) and After (Mdn = 5, n = 18), Z = -2.5, p = .012, r = -0.7. Frustration data satisfies the assumptions of normality and homogeneity of variances, allowing for the use of paired t-tests. The paired t-test for Frustration indicated a non-significant small difference between Before (M = 10.1, SD = 3.8) and After (M = 8.6, SD = 5.3), t(19) = 1.4, p = .169.

6.2 Task completion time

In terms of task completion time, the Shapiro-Wilk test for normality showed that both the data from the previous version and the revised version had p-values of 0.06876 and 0.0782, respectively, which are greater than 0.05. Thus, it can be considered that the data follows a normal distribution. Furthermore, when examining homogeneity of variances using One-Way ANOVA, the obtained p-value was 0.1103, which is greater than 0.05, indicating that the data satisfies the assumption of homogeneity of variances. Therefore, we performed a paired t-test to compare the task completion time, and the resulting p-value was 0.04392, indicating a certain level of significant difference.

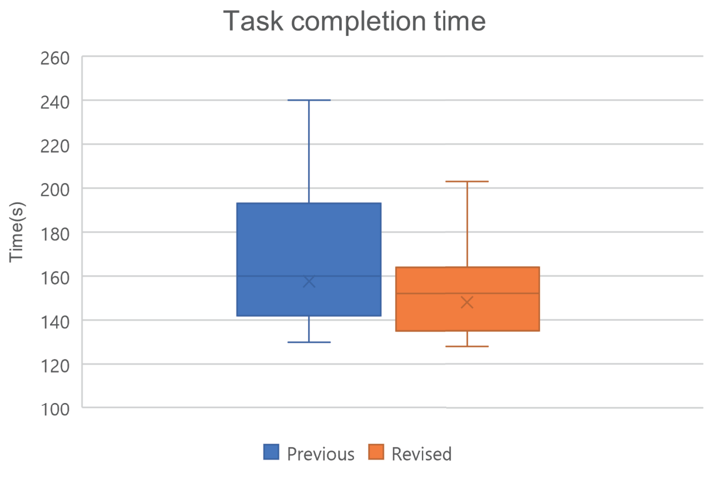


Figure 36: Task completion time

6.3 Feedback and insights

After completing two driving experiments, we conducted short interviews to gather feedback. The interviews aimed to collect opinions on several topics related to evaluating the two test beds and obtaining overall feedback on the mobility vehicle experience. We utilized the insights gathered from the feedback and observations to be described in the *Discussion* section. The interview questions were categorized as follows:

1. Differences in specifications
2. Challenging tasks in each test bed
3. Footplate design
4. Others

Table 8: Interview responses

Category	Version	Interview responses
Specification	Previous	*"In the previous version, the legs were designed to be folded a lot, so the thighs were tense and the legs felt tired, making driving uncomfortable."(P15, P19)*
	Previous	*"In the previous version, although the sitting posture was uncomfortable, it was good for operating precisely."(P6, P13)*
	Previous	*"In the previous version, it can be particularly uncomfortable for tall and long-legged people"(P7)*
	Revised	*"In the improved version, the sitting posture was much more comfortable and stable."(P1, P5)*
	Revised	*"In the improved version, less thigh force was required for steering, and changing direction was easier."(P16, P20)*
	Common	*"The distance of the footrest makes it difficult to operate delicately, change direction, and control speed."(P7)*
Tasks	Previous	*"In the previous version, the leg had a heavy load during rotation."(P2, P9)*
	Previous	*"It would be better to increase rotation sensitivity for the previous model."(P2)*
	Revised	*"In the improved model, less thigh strength was required, and the rotation tasks were easier compared to the previous version."(P13, P16)*
	Common	*"It was difficult to drive backward because there is a difference in the degree of rotation between forward and backward."(P2, P14)*
	Common	*"It was difficult to drive backward in both models."(P16)*
Footplate shape	Previous	*"The previous footplate had a flat shape, requiring more strength for the legs."(P4)*
	Previous	*"The previous footrest did not provide a stable footing."(P3, P18)*
	Revised	*"The improved design provided a much better sense of stability and a more comfortable attachment."(P7)*
	Revised	*"In the improved version, it is difficult to drive backward when wearing slippers."(P1, P6)*

Category	No.of Participant	Interview responses
Footplate shape	Revised	*"The improved footplate provided a comfortable and controllable surface for the feet. When exerting force on the ankles, the posture felt more natural."(P12, P17)*
	Revised	*"In the case of the improved footplate, while the angle was suitable, people with larger feet might have felt instability due to the fixed position of the heel on a smaller footplate."(P3)*
	Revised	*"It is difficult to control the distance precisely by pulling the heel."(P9)*
	Revised	*"While applying force to the heel is easier, exerting force on the forefoot allows for more precise adjustments."(P2)*
	Common	*"It seems that the footplate shape does not have a significant impact on driving performance."(P7)*
Others	Previous	*"The previous model provided stability due to the low center of gravity."(P13)*
	Revised	*"The handle height was relatively lower in the improved version of the prototype"(P6)*
	Revised	*"Having an elevated sight contributes to a comfortable feeling."(P8)*
	Common	*"Backward driving rotation was confusing since the direction of rotation between AngGo and the car is opposite."(P3, P9, P15, P17)*
	Common	*"Consistency in the steering direction is required."(P11)*
	Common	*"Backward driving was difficult since it was hard to look back"(P4, P8)*
	Common	*"It would be more stable if the handle was in front."(P2)*
	Common	*"The brake system that returns the footplate position to its original makes it difficult to operate in emergencies."(P6)*
	Common	*"I feel the mobility control itself comfortable standing on a kick scooter or bicycle."(P8)*
	Common	*"I felt uneasy during the initial ride because my attention was constantly focused on the footplate, making it difficult to see ahead."(P20)*
	Common	*"It seems that there is a lack of feedback for forward and backward movements. It would be beneficial to have physical and visual feedback."(P15)*

VII Discussion

7.1 About 6 variables of NASA TLX

Consequently, through revised specifications and a new footplate design, it was observed that there was a significant reduction in physical demand and effort. With the increased knee angle in the revised specifications, the default posture in the stationary state became more comfortable, and there was a noticeable decrease in physical strain when moving the legs for rotation. There appeared to be a significant difference in physical demand during tasks involving curves, primarily because in the existing design, where the knees drop vertically, there is a greater burden on the legs during rotation. One possible solution to reduce this burden, while still using the existing dimension, would be to adjust the sensors to be more sensitive, allowing for rotation without requiring excessive leg movement.

Regarding mental demand and temporal demand, there were no significant differences between the two prototypes. This is attributed to the fact that the driving control method did not change significantly, resulting in similar driving outcomes between the two testbeds. As for performance, there were no significant differences observed. It is hypothesized that factors influencing performance are not only the specifications and footplate design but also the experience time and familiarity with the driving operation. Despite conducting sufficient practice sessions before the experimental sessions, the first session, which is difficult to adapt to due to different driving styles in various situations, and the repeated second session may have influenced the performance results. Examining the data from Group A and Group B(Group B drove the improved version first), all other data showed a decrease in average demand for the improved specifications. However, in the performance data of Group B, there was little difference in average performance between the two testbeds. It is speculated that driving the improved version initially provided a relatively good performance experience, leading to satisfactory performance even with the existing specifications as participants became more accustomed to the driving.

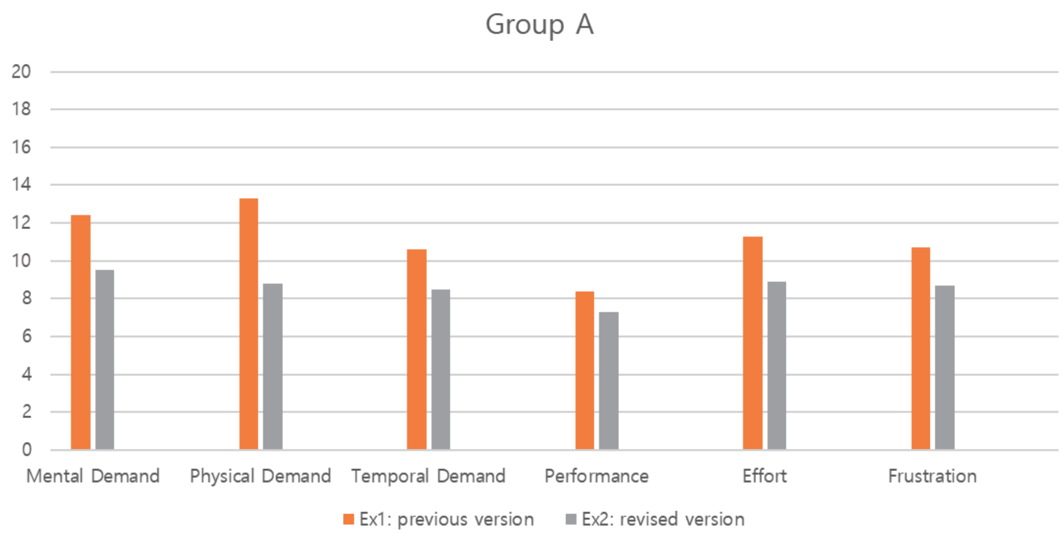


Figure 37: NASA TLX result of group A(drive the previous version first)

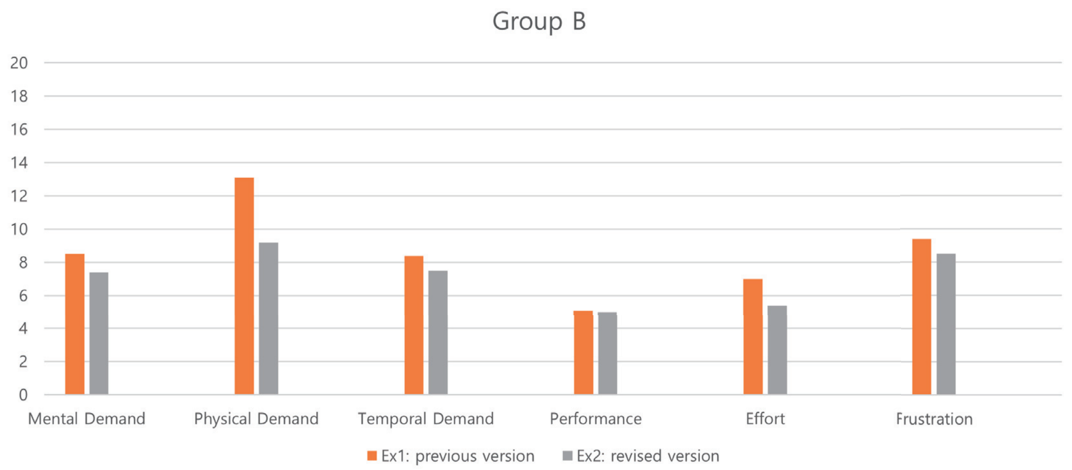


Figure 38: NASA TLX result of group B(drive the revised version first)

Frustration scores were relatively high for some participants in the improved version. The factors contributing to these scores included the difficulty of reverse maneuvers when wearing slippers and the increased discomfort due to the relatively lower armrest resulting from the higher seat height. When wearing slippers or similar footwear that causes the feet to slide and separate from the shoes, during reverse maneuvers, the shoes may catch on the footplate, but before the force is transmitted to the footplate, the feet tend to slip, resulting in increased strain on the legs during reverse motion.(Figuer 39)

Furthermore, during the process of adjusting the seat height for the revised testbed, the backrest was adjusted higher together, but the armrest height was not adjusted with them(Figure 40). As a result, when boarding the testbed of the revised version, the armrest height was lower compared to the original seat-armrest height, causing inconvenience in gripping the armrest or insufficient coverage of the armrest from side to side, which led to increased anxiety and higher frustration scores. When improving AngGo's seat height, it is necessary to simultaneously increase the heights of the armrest and backrest as well.

Figure 39: Case of wearing slipper

Figure 40: Different height of seat to armrest

Figure 41: Cases of using the balls of their feet to control

7.2 Insights of feedbacks

The feedback from the interviews revealed that most participants agreed on the increased comfort resulting from the changes in dimensions. However, there were several issues raised regarding the change of the footplate design. Feedback indicated that while it was convenient to use the heels to pull the footplate, during reverse maneuvers or when performing delicate maneuvers involving rotation, participants tended to use the balls of their feet for control (P2, P9). Since the number of reverse tasks in the experiment was limited, it is possible that participants had not fully mastered the use of the heels for precise control. Further investigation is needed to determine the factors that make delicate control challenging. Although some participants mentioned difficulties with delicate control, there was consistent feedback regarding the discomfort associated with the previous footplate design and dimension. Given the experimental results and feedback indicating the significant alleviation of this discomfort through the improved dimension, it is recommended to use the revised footplate design employed in the experiment while incorporating auxiliary measures for refined control, such as sensitivity adjustments for rotation during backward driving or motor output modulation.

Furthermore, it is true that the improved version resulted in reduced physical demand, but there were also reactions indicating initial difficulty in speed control due to the increased ease of pushing. In fact, several participants were observed to push forcefully at the maximum intensity or have difficulty in speed control when starting the experiment with the improved version(Group B). Similar insights were provided, stating that while the previous prototype was uncomfortable, the control became more delicate. Feedback regarding the sensitivity and precision of control seems to be influenced by the incomplete implementation of hardware in the testbed. Furthermore, addressing the discomfort associated with control precision can be achieved by refining the mapping of sensor values to motor output values and conducting a user study to investigate user intentions and the actual rotation angles of mobility during reverse maneuvers within the improved dimension.

7.3 Limitation and further works

In terms of limitations, there are experimental limitations and conceptual limitations. In terms of the experiment, there were implementation issues and the inability to standardize the floor-seat height. Firstly, the implementation issues arose from attempting to use the same hardware conditions in two testbeds by incorporating additional assembly into the existing AngGo frame. However, due to the old suspension structure, there were instances of instability during abrupt stops and starts. Additionally, the caster's form resulted in unintended rotation during straight reverse movement or the inability of the caster to rotate fully due to insufficient motor output. The suspension structure is planned to be improved in the development of the new AngGo version, and the rotating caster can be replaced with a caster that has a shorter distance between its rotation axis and the point where the wheel touches the ground, along with adjusting the motor output to resolve these issues. The two testbeds had a significant difference in floor-seat height because the testbeds were assembled by adjusting the seat height based on modifying the footplate-seat height(H). With the improved dimensions, a profile was assembled to modify the footplate distance(L), resulting in a 6cm increase in footplate height and a 9cm increase in seat height(floor-seat) to conduct the experiment with a footplate-seat height(H) of 40.5cm. This difference in eye level and the inability to maintain the same armrest height may have affected the evaluation metrics, including frustration.

On the conceptual side, a limitation exists regarding the discomfort of footplate manipulation for certain users. While the improved footplate design was helpful in reducing leg demand according to the experiment results and feedback during interviews, it may not be suitable for users wearing slippers or high heels. The target context is large indoor spaces including large airports or convention centers, where users wearing slippers may be less common. However, high heels could pose difficulties in footplate manipulation through sliding. The AngGo and SISM concepts target individuals experiencing discomfort when walking in spacious indoor areas, so those wearing high heels could potentially be users of indoor mobility vehicle solutions. However, in the case of footplate control, factors such as foot-seat height and ankle angle, which affect user comfort, can significantly differ when wearing heels compared to typical cases. Therefore, controlling the platform using the feet could be a limitation in cases where users wear high heels or slippers. Developing additional designs for a comfortable foot-controlled method, regardless of the type of footwear (heels, slippers, etc.), could be considered as further work.

Improving the grip between the footplate and the foot can help alleviate the discomfort associated with different types of footwear. This can be achieved by adding structures that hold the foot or by increasing the friction between the foot and the footplate. While incorporating straps or foot covers to hold the foot to the footplate may enhance foot stability in manipulation, it is important to consider the mobility vehicle characteristic, where the form to quickly disengage becomes crucial in emergency situations. Therefore, designs that restrict the upper part of the foot and fix it in place may pose risks. If designing the foothold structures in further works, designs aimed at holding the foot should allow for easy removal in emergency situations, to prevent secondary accidents. In the experiments, both footplates used were made of plastic material on the surface where the foot contact. However, using a material with higher friction on the footplate would be beneficial for better force transmission between the foot and the footplate. This consideration should be aligned with the overall design and CMF (Color, Material, and Finish) of the mobility vehicle.

AngGo is an indoor shared mobility vehicle, where users can board and utilize AngGo when needed within indoor spaces. While the research and design focused on creating a comfortable specification suitable for public shared mobility vehicles, where most people can easily use it, it may be necessary to consider adjustable seat height in cases of prolonged use or individual ownership of the mobility vehicle. Depending on the usage environment, user types, and development costs, incorporating height-adjustment functionality in future AngGo development could be a viable consideration.

VIII Conclusion

This study was conducted to reduce physical demand during operation and enhance the usability of the foot-operated control method of the shared indoor smart mobility vehicle, AngGo. In order to achieve this research objective, three research questions were formulated: What factors contribute to leg strain in the existing AngGo design? How can the footplate control system be redesigned based on the factors of the first research question? Does the revised design effectively reduce physical demand?

To investigate which factors influence physical demand, feedback was collected from three designers who experienced the existing AngGo control method. The feedback revealed insights suggesting that reducing leg strain could be achieved by finding a comfortable footplate distance and modifying the footplate shape for comfortable reverse movement.

Since AngGo serves different purposes and is used differently than chairs or car seats, an investigation was conducted with 30 participants to identify suitable dimensions for footplate manipulation on AngGo. The comfort footplate-seat height, backrest-footplate origin distance, and maximum and minimum distance were investigated. The results showed that the average footplate-seat height was 40.5cm, the average backrest-footplate origin distance was 59cm, and the average of the minimum and maximum values was 48.5cm and 66.2cm, respectively. The existing footplate system could move a maximum of 12cm in total, 6cm in each forward and backward direction. When the average footplate distance was set to 59cm, it fell within the comfortable range of the minimum and maximum values. Furthermore, by incorporating the range of joint motion in the modified mobility dimensions and utilizing the findings from desk research, we calculated the optimal ankle angle for comfort. Based on these dimensions, the vehicle design was improved.

To validate whether the improved dimensions and footplate design can effectively reduce physical demand, a usability evaluation was conducted with 20 participants. A comparative experiment was carried out using the existing frame of AngGo and an assembled prototype based on the improved dimensions, and the NASA Task Load Index (TLX) was used as the evaluation scale. The results showed significant differences in physical demand and effort, and the feedback received positive evaluations for the improved design.

In conclusion, the modification of dimensions reduced physical strain during driving a mobility vehicle. Furthermore, proposing the investigated comfort range of dimensions and compact internal structure of the footplate mechanism could provide an opportunity to broaden the design freedom for foot-operated personal mobility vehicles.

References

Bianchessi, A. G., Ongini, C., Boniolo, I., Alli, G., Spelta, C., Tanelli, M., and Savaresi, S. M. (2014). A novel electric vehicle for smart indoor mobility. *IEEE Transactions on Intelligent Transportation Systems*, 15(4):1429–1440.

Carrozza, M. C., Persichetti, A., Laschi, C., Vecchi, F., Lazzarini, R., Vacalebri, P., and Dario, P. (2007). A wearable biomechatronic interface for controlling robots with voluntary foot movements. *IEEE/ASME Transactions on Mechatronics*, 12(1):1–11.

Fitt, H. and Curl, A. (2020). The early days of shared micromobility: A social practices approach. *Journal of Transport Geography*, 86:102779.

Hart, S. G. and Staveland, L. E. (1988). Development of nasa-tlx (task load index): Results of empirical and theoretical research. In Hancock, P. A. and Meshkati, N., editors, *Human Mental Workload*, volume 52 of *Advances in Psychology*, pages 139–183. North-Holland.

Kang, D., Park, H., Kwak, Y., Kim, B., Kim, S., Kim, D., Lee, S., Kim, B., and Lee, H. S. (2020). Development of a shared indoor smart mobility platform based on semi-autonomous driving. In *2020 29th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, pages 963–970.

Kyung, G. and Nussbaum, M. A. (2009). Specifying comfortable driving postures for ergonomic design and evaluation of the driver workspace using digital human models. *Ergonomics*, 52(8):939–953.

Lee, J. D., Wickens, C. D., Liu, Y., and Boyle, L. N. (2017). *Designing for people: An introduction to human factors engineering*. CreateSpace.

Lee, S.-h. (2019). Hug2go: The development of indoor smart driving personal mobility.

Lin, M. C.-L. (2021). *Affordable autonomous lightweight personal mobility*. PhD thesis, Massachusetts Institute of Technology.

Nielsen, J. and Landauer, T. K. (1993). A mathematical model of the finding of usability problems. In *Proceedings of the INTERACT'93 and CHI'93 conference on Human factors in computing systems*, pages 206–213.

Park, S. J., Kim, C.-B., Kim, C. J., and Lee, J. W. (2000). Comfortable driving postures for koreans. *International Journal of Industrial Ergonomics*, 26(4):489–497.

Pearson, G. and Weiser, M. (1986). Of moles and men: The design of foot controls for workstations.

SIGCHI Bull., 17(4):333–339.

Roaas, A. and Andersson, G. B. J. (1982). Normal range of motion of the hip, knee and ankle joints in male subjects, 30–40 years of age. *Acta Orthopaedica Scandinavica*, 53(2):205–208. PMID: 7136564.

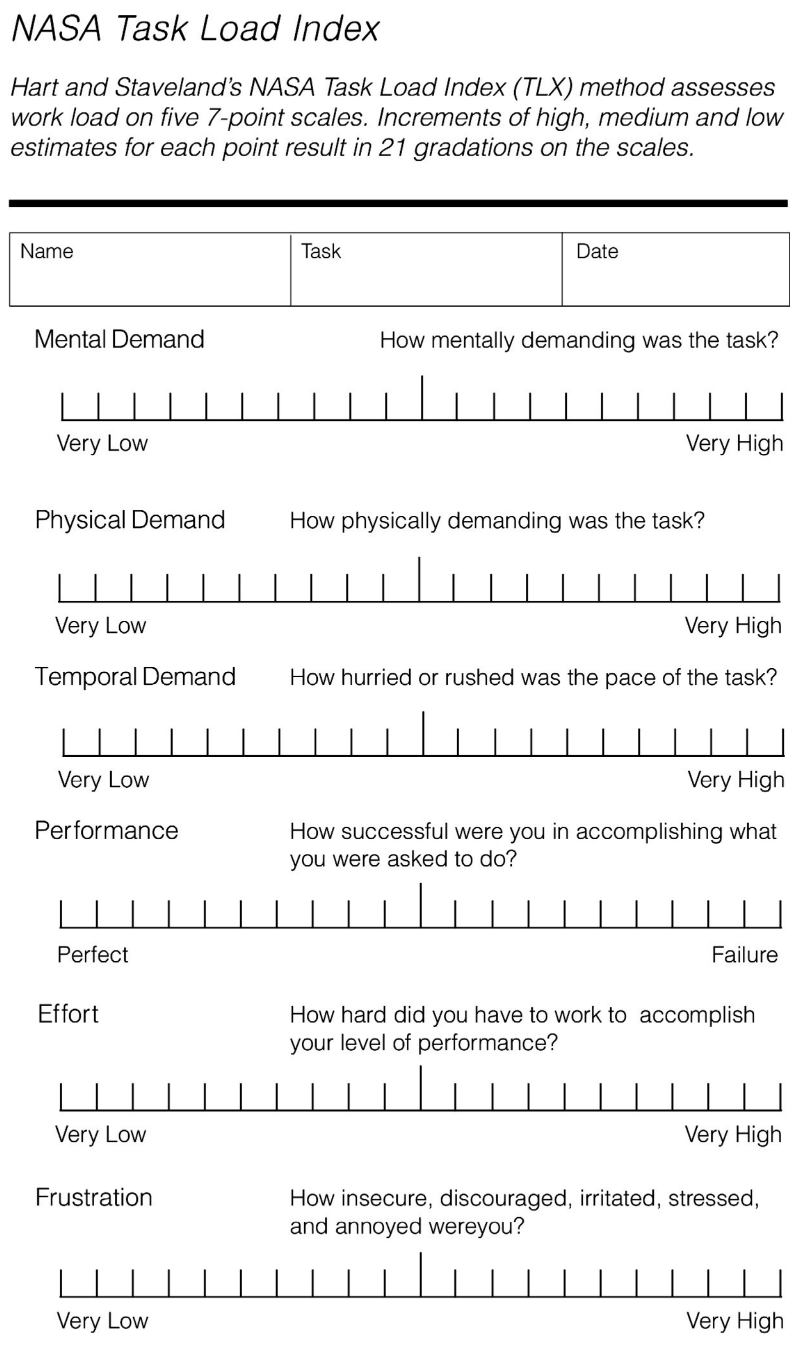
Schmidt, D., Ramakers, R., Pedersen, E. W., Jasper, J., Köhler, S., Pohl, A., Rantzsch, H., Rau, A., Schmidt, P., Sterz, C., Yurchenko, Y., and Baudisch, P. (2014). Kickables: Tangibles for feet. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '14, page 3143–3152, New York, NY, USA. Association for Computing Machinery.

Song, J. and Kim, Y. (2017). Driving performance evaluation using foot operated steering system in the virtual driving simulator. *Journal of Biomedical Engineering Research*, 38(4):197–204.

Springer, J. and Siebes, C. (1996). Position controlled input device for handicapped: Experimental studies with a footmouse. *International Journal of Industrial Ergonomics*, 17(2):135–152.

Velloso, E., Schmidt, D., Alexander, J., Gellersen, H., and Bulling, A. (2015). The feet in human–computer interaction: A survey of foot-based interaction. *ACM Comput. Surv.*, 48(2).

Appendix



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure 42: Questionnaire of NASA TLX scale

Acknowledgements

이 연구와 AngGo 및 새로운 모빌리티 연구 전반을 적극적으로 지원해주시고 지도해주신 이희승교수님께 감사의 말을 전합니다. 교수님과 DECS 연구실 덕분에 아이디어뿐이었던 새로운 모빌리티가 실현될 수 있었습니다. 만들고 싶은 제품을 만들 수 있고, 생각을 정말로 실현시킬 수 있었던 연구실에서의 4년 반의 시간은 저에게 굉장히 뜻깊고 값진 시간이었다고 생각합니다. 교수님의 지도와 연구실 식구들의 도움으로 다른 곳에서는 쉽게 할 수 없는 경험을 할 수 있었습니다. 제가 개인적으로 힘들었던 시기에도 계속 저를 신경써주시고 챙겨 주신 이희승교수님 덕에 석사과정을 잘 마무리할 수 있었던 것 같습니다.

연구와 논문자료 제작에 많은 도움과 조언을 준 다빈, 프로토타입 구동에 많은 도움을 주신 승호씨, (권)민지씨, 또 힘들 때 옆에 있어주고 힘낼 수 있게 응원해준 민재씨와 (최)민지 학생에게도 정말 고맙습니다. 함께 졸업준비를 하며 도와준 지연, 연구실에서 저를 챙겨 주셨던 승빈씨와 우인씨 그리고 AngGo의 개발을 함께 해준 하은씨, 건호선배, 병헌선배, 동훈선배, 성범선배에게도 감사를 표합니다. 제가 힘들었던 시기에 연구실 식구들에게 폐를 끼친 것 같아 미안하고, 그럼에도 많이 도와주고 신경 써준 연구실 식구들 모두에게 정말 감사하고 고맙습니다. 제가 힘들어서 주변에 소홀할 때도 늘 격려해주고 옆에 있어주었던 디자인학과 동기들과 친구들, 특히 한솔, 도진에게 고마움을 표합니다. 덕분에 포기하지 않고 석사생활을 완주할 수 있었고, 회복할 수 있었습니다. 감사의 인사를 전할 사람이 너무나도 많지만 이쯤에서 줄이도록 하겠습니다.

마지막으로 사랑하는 가족, 어머니, 아버지, 동생, 그리고 나를 아끼고 좋아해준 사람들 덕분에 힘든 와중에도 하루하루를 힘내어 버틸 수 있었다고 말하고 싶습니다. 학부인턴과 석사생활 총 4년 반이라는 기간동안 재밌는 많은 프로젝트를 하며 좋은 경험을 할 수 있었고, 좋은 사람들을 만나 더 성장하는 기간이 되었습니다. 모두에게 정말 감사합니다.