A recreational basketball wheelchair with adjustable seat width

FitConnect

TU Delft Delft University of Technology

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MSc Integrated Product Design

Graduation Project by **Hengrui Zhao**

Me pushing the wheelchair in the elevator

Acknowledgement

The project has been a long journey to me, like pushing the heavy and fragile wheelchair in a huge maze. It was never easy, but I managed to find my way out with all the help and kindness from others along the way. And at this particular moment I would like to express my appreciation towards these people.

I would like to extend my sincere gratitude to the supervisory team. Thanks to Arjen, whose guidance has contributed more than anyone else to my current development as a designer. I will never forget to think in a designer way. And thanks to Katherine, who provided detailed and thoughtful feedback, helped me think more logically and become a better researcher. I'm not sure if I deserve all these, but it's my honor to have you two as my supervisors.

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Thanks to my friend Darcy, who cooked me nice meal and encourage me. To Joao and Julian, who provided precious insights and suggestions to help me out. Also to my parents, who were able to understand my struggle and support me. And to all my friends from home and abroad whose support and encouragement infused me with strength and motivation.

This long journey was never easy to me, but with all the help in the world, it became more enjoyable and meaningful than any other design project in my past career.

Content

TUDelft IDE Faculty, where everything happened

01 Introduction

1.1 Introduction

Wheelchair basketball, the most popular wheelchair sport, plays a vital role in promoting inclusion and physical engagement among wheelchair users. However, despite the availability of government and institutional subsidies in the Netherlands, the processes of funding, customization, and maintenance remain lengthy and complex, mainly due to the high cost and extensive customization required for specialized wheelchairs. Users' fitting needs, particularly among newcomers and teenagers, are constantly changing, yet the limited accessibility and adjustability of existing wheelchairs often forces players to rely on poorly fitted or no longer suitable, shared, or previously used equipment, creating notable pain points in comfort and performance.

In response to these situations, this thesis proposes improvement in recreational basketball wheelchair adjustment level and make it possible to adapt to rapid changing fitting requirements and accommodate a wide variety of users over time.

1.2 Assignment

Problem Definition

The usage and lifecycle demands of recreational basketball wheelchairs extend beyond their original design scope of static fitting for one single user, as they must accommodate evolving individual fitting needs and multiple users. Thus, static configurations or limited adjustability are inadequate, highlighting the need for adaptable solutions and services that ensure sustained fit.

Design Vision

This design envisions a recreational basketball wheelchair that can be adjusted and refitted many times over its lifespan. Able to adapt to changing body dimensions and skill level, even new users. The solution should not adding too much additional cost, weight or complexity to the individual wheelchair. In this case players are less likely to buy a new wheelchair but tend to adjust the old one when unfit occurs. The design will help get more people involved in and able to enjoy the sport of wheelchair basketball, and also help organizations to get more active in the sport.

Goal

Design to improve recreational basketball wheelchair, allowing it to be adjusted and refitted multiple times throughout its lifespan, ensuring sustained fitting for different users and rapid changing needs.

1.3 Approach

The project will be carried out following the double diamond model (Figure 1.1), which include four basic phases, research & analysis, synthesis, ideation and implementation.

Discover & Define

In the discover phase, market research, ergonomics and user study are repeated and mutually verified. After fully expanding the problem scenario, key user pain points and use cases are identified, and a list of requirements is integrated to ultimately arrive at a clear design brief.

Develop

Starting from the design brief, brainstorm session on design solutions was carried out based on different adjustment dimensions, and then integrate them into multiple design concepts based on morphological chart.

Based on these design concepts, more prototype tests and practices were carried out to asses their value. Finally, the ideal concept was selected for further development to be further refined and implemented.

Deliver

With in the scope of the selected concept, several generation of prototypes were iterated and tested to narrow the design and realize a final prototype that can be used for testing. Through real user testing feedbacks and insights, the value of the design was verified and directions for further optimization were explored.

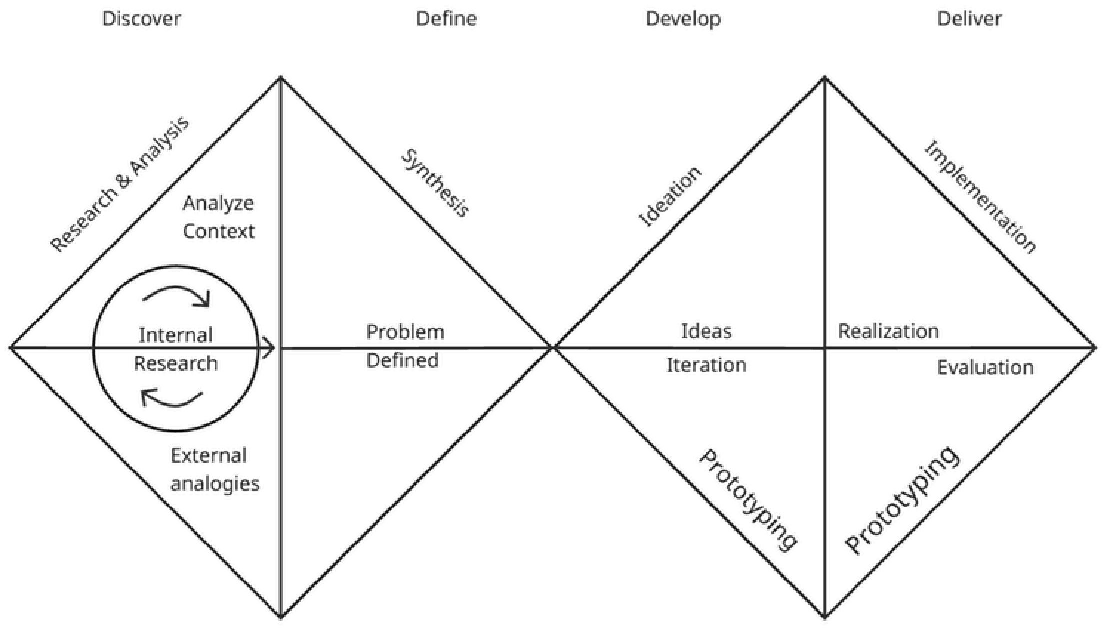


Figure 1.1 Double Diamond Model

Basketball wheelchairs prepared along the doorway before the training session

02 Research & Analysis

2.1 Current Products

To further explore the basketball wheelchair industry, existing product designs and customization processes were reviewed across relevant brands and manufacturers.

The price distribution of available Basketball Wheelchairs products is very concentrated, with the majority of products priced in the €3,000 to €4,000 range. Highly customized wheelchairs incorporating advanced technology for professional athletes can cost up to €10,000. And takes months to be manufactured. However, basketball wheelchairs manufactured on a large scale in China cost as low as €600.

From the overall analysis of existing products, the basketball wheelchair industry is characterized by a high degree of product homogenization, with many designs highly similar or unchanged for many years, and only a few companies with unique outputs and evolution process, further information will follow.

In summary, this section reviews the current adjustable features and their ranges of adjustment in basketball wheelchairs, identifies gaps in adjustability, and outlines the underlying user needs that inform subsequent design considerations.

RGK Sport

RGK Sport from Sunrise Medical, which has a contractual partnership with the Rotterdam municipality, is well recognized and widely adopted among players. It has the largest number of basketball wheelchair models and the longest product line length among the brands covered in the research. Starting at €2,200 for entry-level club sports, then moving on to the later €4,000 All-Star series, and the €8,000 Elite series for professional athletes (see Figure 2.1). Its product line offers a gradual growth path for players of varying skill levels and needs, contributing to its leading position in the market.

RGK's wheelchairs have very few adjustment features, but it is worth noting that, in order to accommodate the evolving needs of beginners as their skills develop, the Club sport model incorporates a sliding anti-tipping wheel frame integrated with the rear wheel axle (Figure 2.2), which allows for adjustment of the center of gravity.

Meanwhile they have an All Court wheelchair, also entry-level wheelchair designed for all kinds of court sports that adjusts the center of gravity, seat height and seat angle through a structure similar to a four-bar mechanism (Figure 2.3).

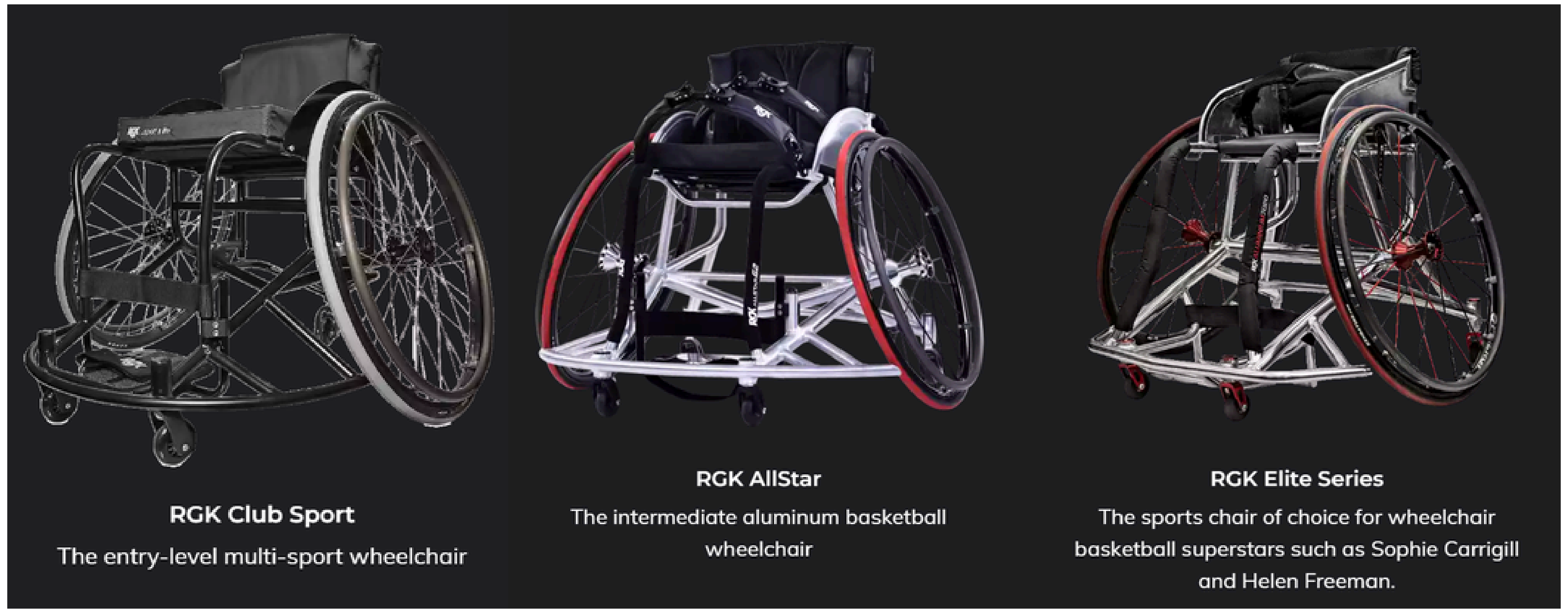


Figure 2.1 RGK Club Sport, RGK AllStar and RGK Elite Series wheelchairs

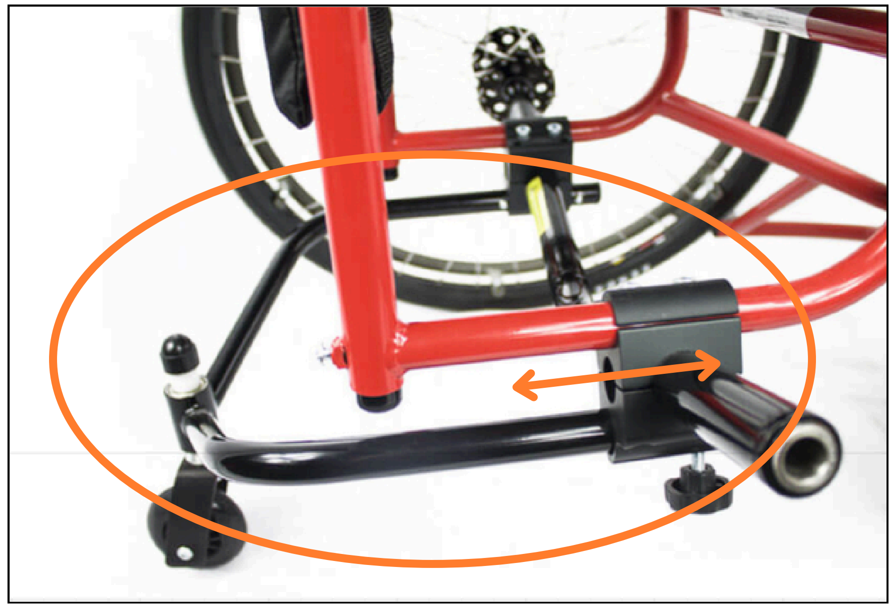


Figure 2.2 Anti-tipping and rear wheel combined parts in RGK Club sport wheelchair

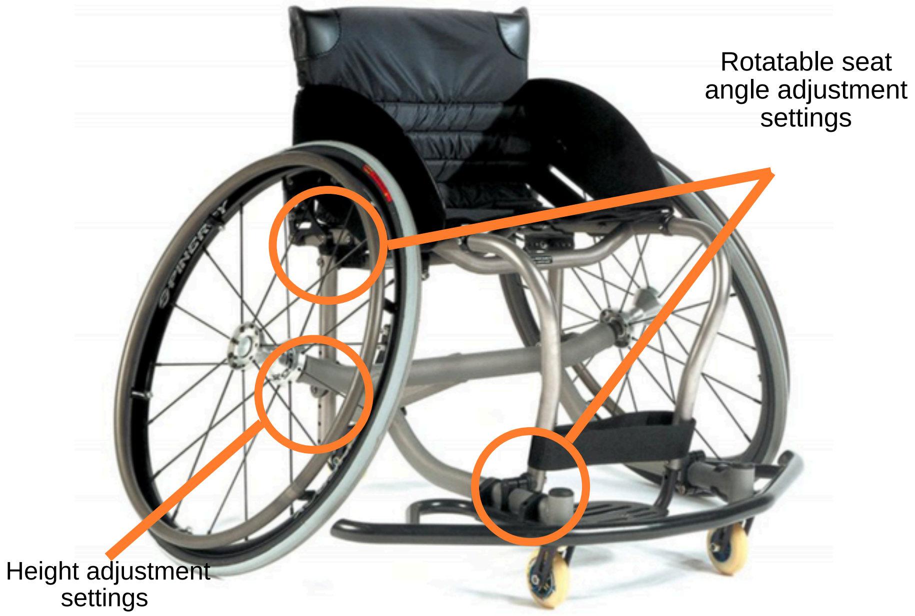


Figure 2.3 Seat height and angle adjustable All Court Wheelchair

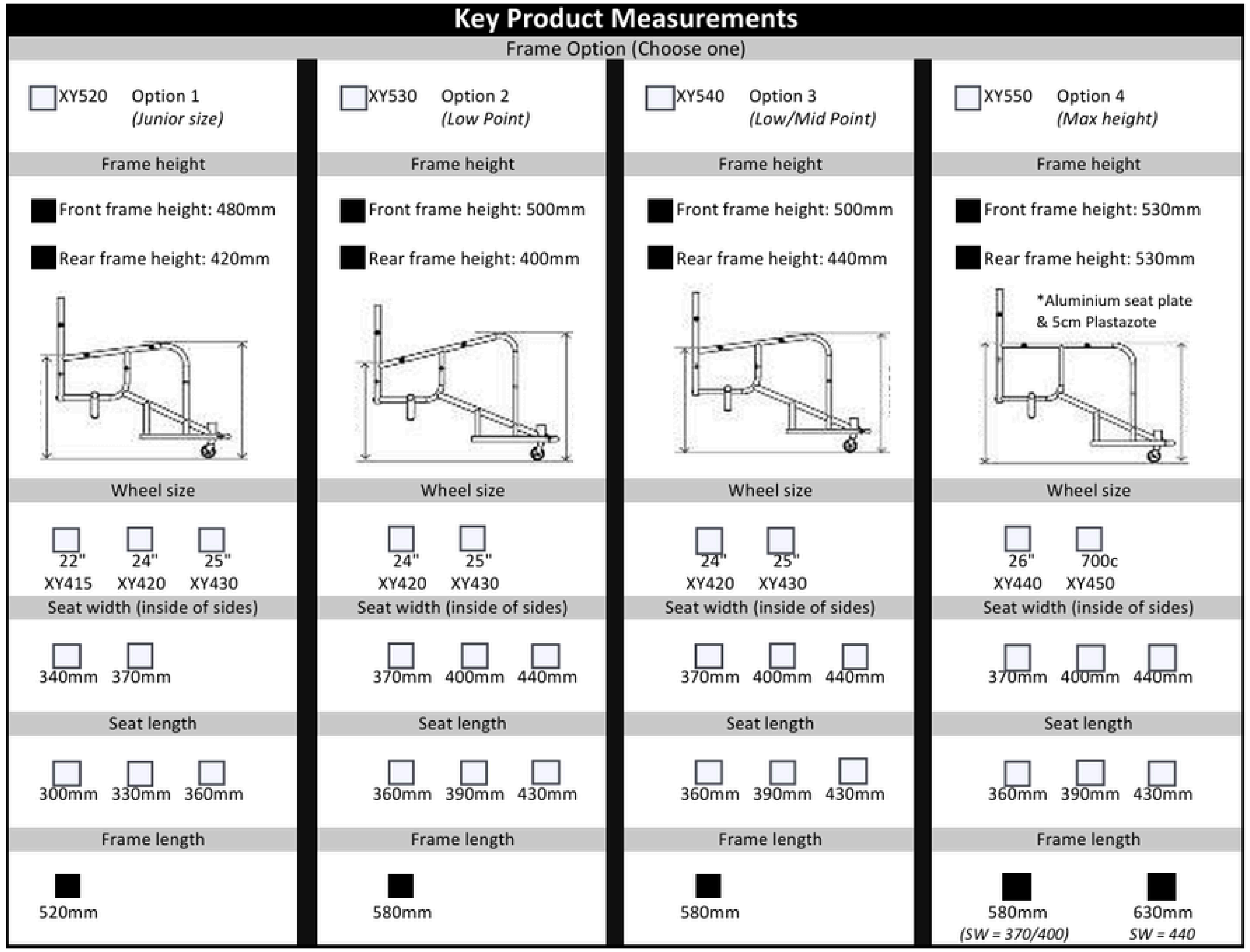
2.1 Current Products

The price variation primarily reflects different levels of customization (shown in the Figure 2.4); higher-cost products like AllStar offer more optional dimensions on the order form compared to Club sports. Also most of them provide minimal scope for subsequent adjustment.

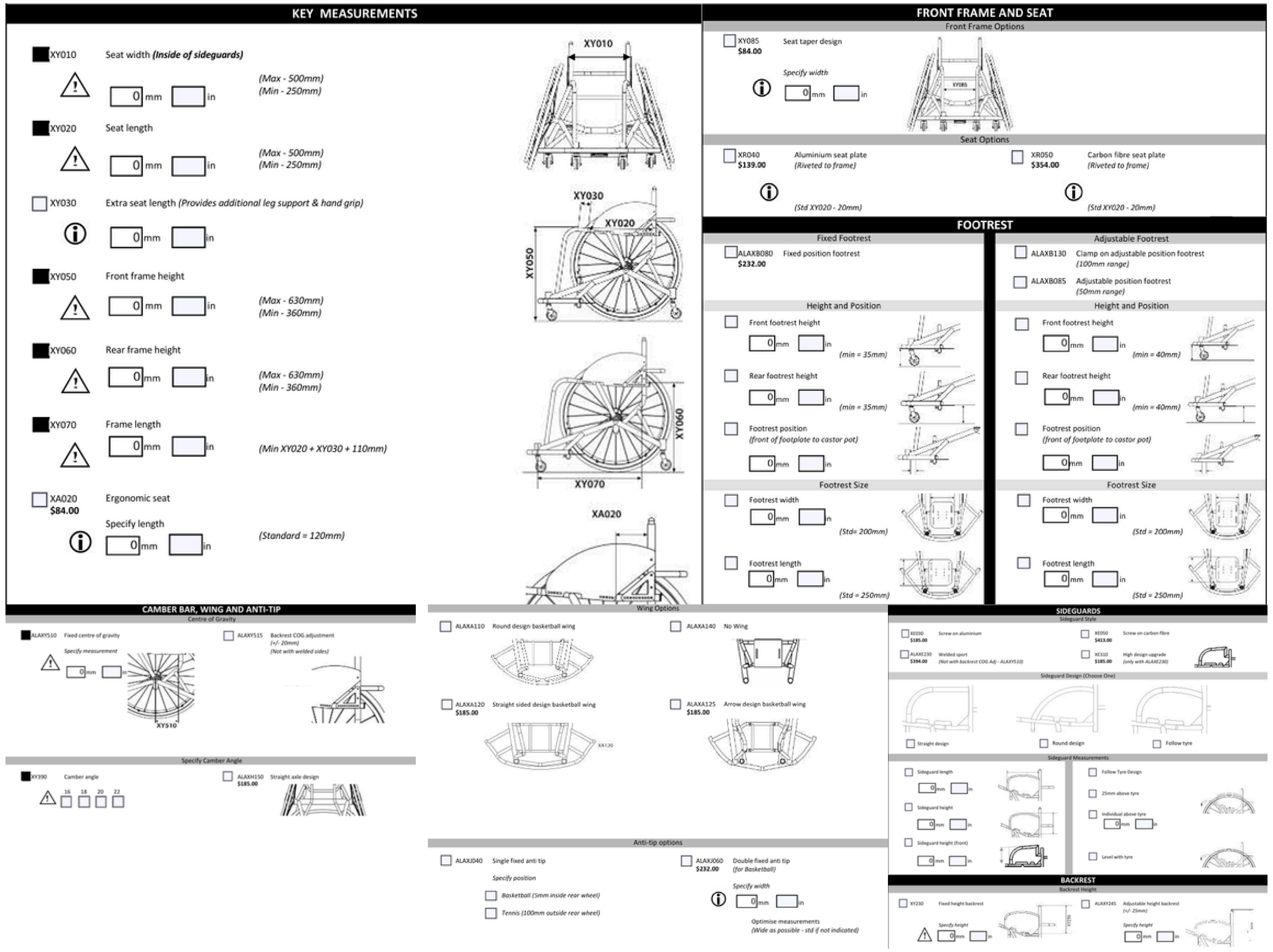
It can be inferred from this is that the lower the degree of customization, the lower the cost. Therefore, with further developed design and manufacturing technologies, reducing the number of customization options and increasing adjustability may contribute to improved accessibility.

Seat and frame heights, seat depths, seat widths and wheel size are the basic and vital dimensions because even the wheelchairs with the lowest custom level include these dimensions for customization.

These dimensions would be ideal if perfectly customized, but are very limited in their ability to adapt to changing needs and new users with different body dimensions.



(a)



(b)

Figure 2.4 Comparison between RGK Club sport measurement (a) and RGK AllStar measurement (b)

2.1 Current Products

Top End Pro

In addition, the Top End company has come up with a unique concept of quick adjustments. This wheelchair (Figure 2.5) was **designed for athletes who want quick and easy adjustments** without sacrificing performance. Not only do adjustments take under 15 minutes, this chair is also simple to order, with just a few key measurements needed.

The structural strength at the joints has been questioned by some users in the later interview session, but it is currently available and used by some players. It is designed so that the seat height and seat angle, backrest angle and seat depth can be quickly adjusted, also reveals a lot potential in having a separate seat designed (Figure 2.6) for basketball wheelchair adjustment.

However, at present, **adjustments can only be made when the user is out of the wheelchair, while seat width remains unaddressed** and still relies on customization in the manufacturing process, with a measurement range of up to 10 inches (Examples of other existing products shown in Figure 2.7).

Figure 2.5 Top End Pro Basketball Wheelchair

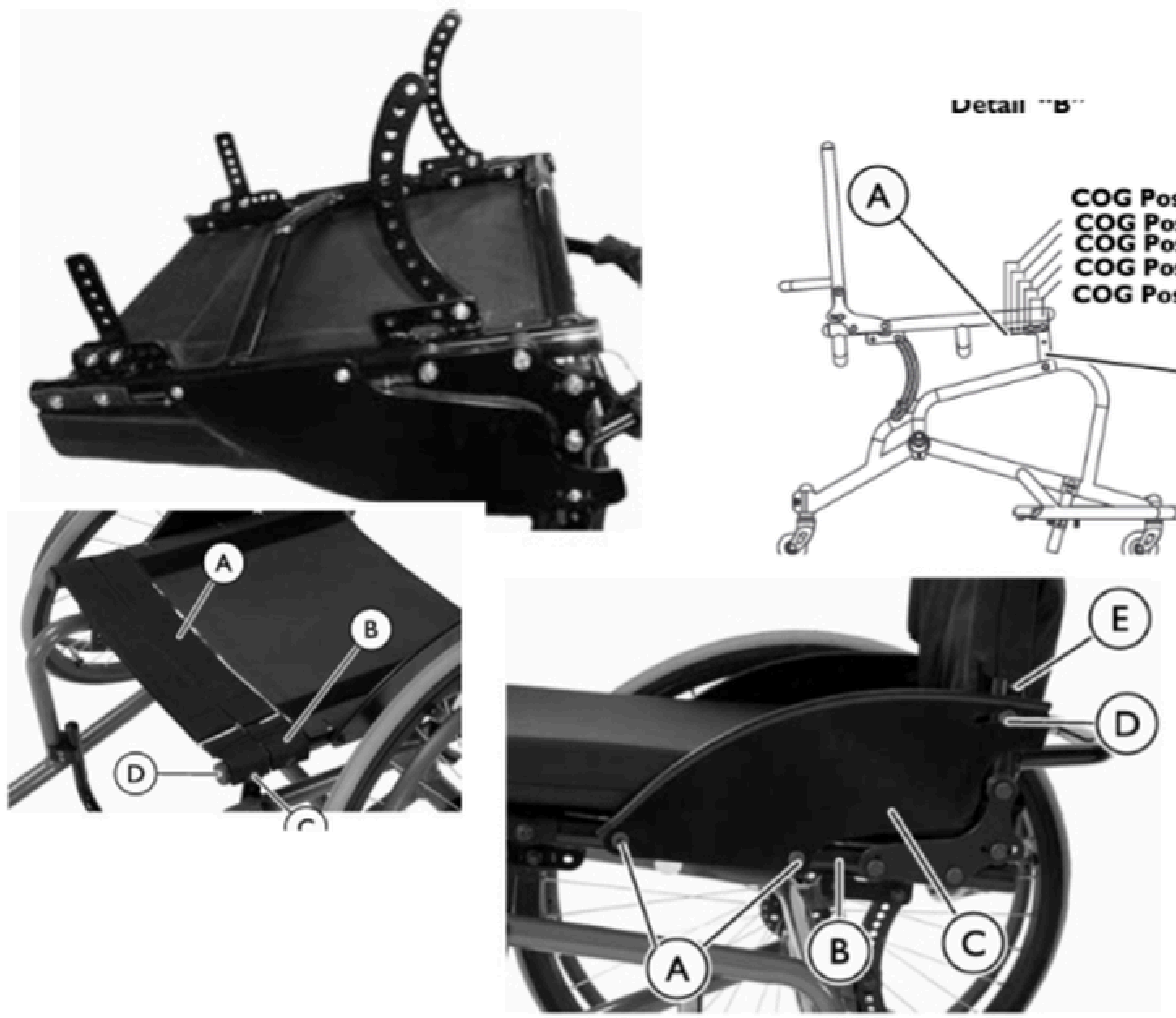
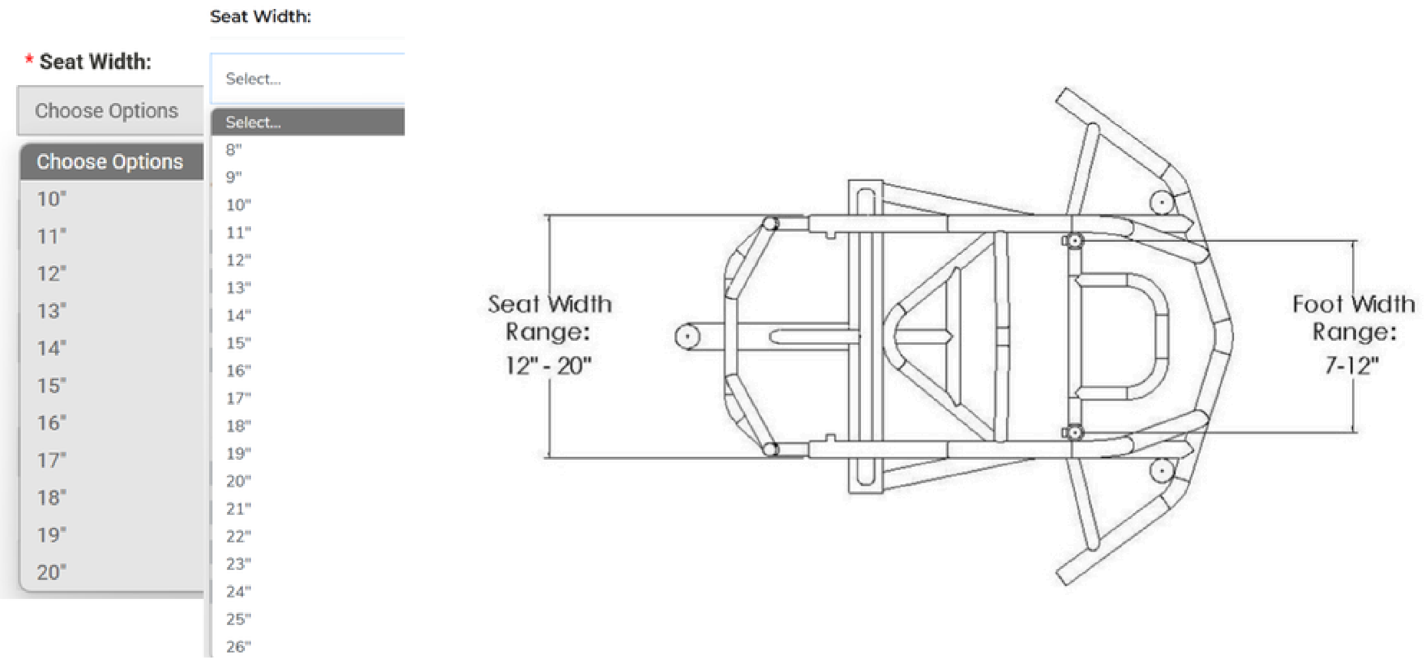


Figure 2.6 Separated seat design create space for adjustment mechanism



(a) (b)

Figure 2.7 Range of seat width measurement in existing products

2.1 Current Products

ROMA Sport

Different from the previous ones, the ROMA Sport focus on developing measurement system called the contour body mapping (Figure 2.8) for better customization. Findings from their user study indicated that **many users, especially after just purchasing, want to alter their wheelchair for better fit.** In response to this phenomenon, they set to work to devise a system with high accuracy that allow the user to experience how the wheelchair would feel before they placed an order.

The system is much more affordable than other already available measuring systems, enables the user to avoid the problem of unfit when they get it at the first place, and also to work with the later adjustment service for secondary adaptation. However, it **cannot shorten the time it takes for subsequent adjustments, nor can it fully simulate real movement scenarios**.

Figure 2.8 The Contour Body Mapping machine in use

PDG Eclipse

Although current basketball wheelchairs lack a seat width adjustment function, in the context of ordinary wheelchairs PDG Mobility has introduced a model called PDG Eclipse with this capability. The adjustment relies on three crossbars with integral holes connected by screws (Figure 2.9). However, the process is complicated and takes quite a lot of effort (Figure 2.10), as it **requires removing all accessories and installing spacers, a new seat plate, and many other additional fittings**.

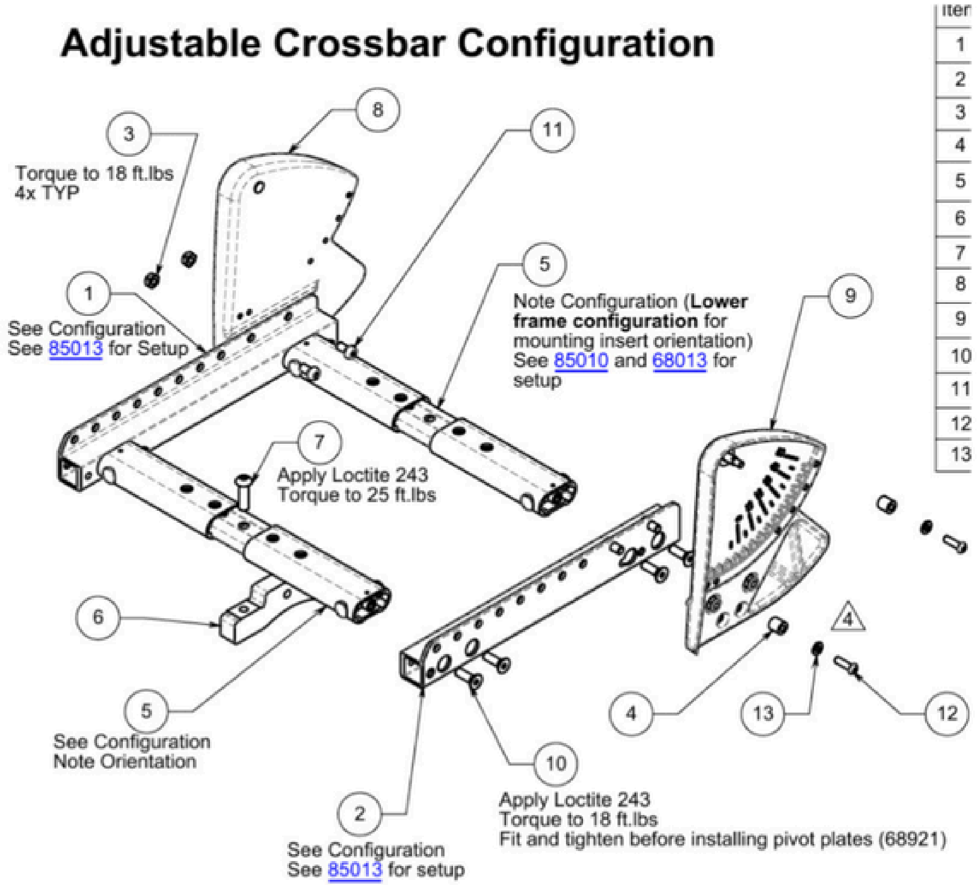


Figure 2.9 Adjustable crossbar drawings in the user manual

Figure 2.10 Scene of the adjusting process in the support video

2.1 Current Products

Dimensions overview

Wheelchairs available on the market can be customized in a wide range of dimensions, all of which shown in Figure 2.11 can be custom made within existing products. Dimensions in orange are already adjustable in some products, while dimensions in blue are currently not adjustable in any of the existing products and can only be custom made at the manufacturing process. All dimensions are listed in the table below.

Adjustable dimensions	Seat Depth Seat Angle Backrest Height Backrest Angle Center of Gravity Front Seat Height Rear Seat Height Footrest Height
Custom made dimensions (Currently not adjustable)	Seat Width Front Wheel Position Detailed Frame Settings (Include but not limit to width, length, height and position of each rod in the lower frame) Camber Angle Rear Wheel Size

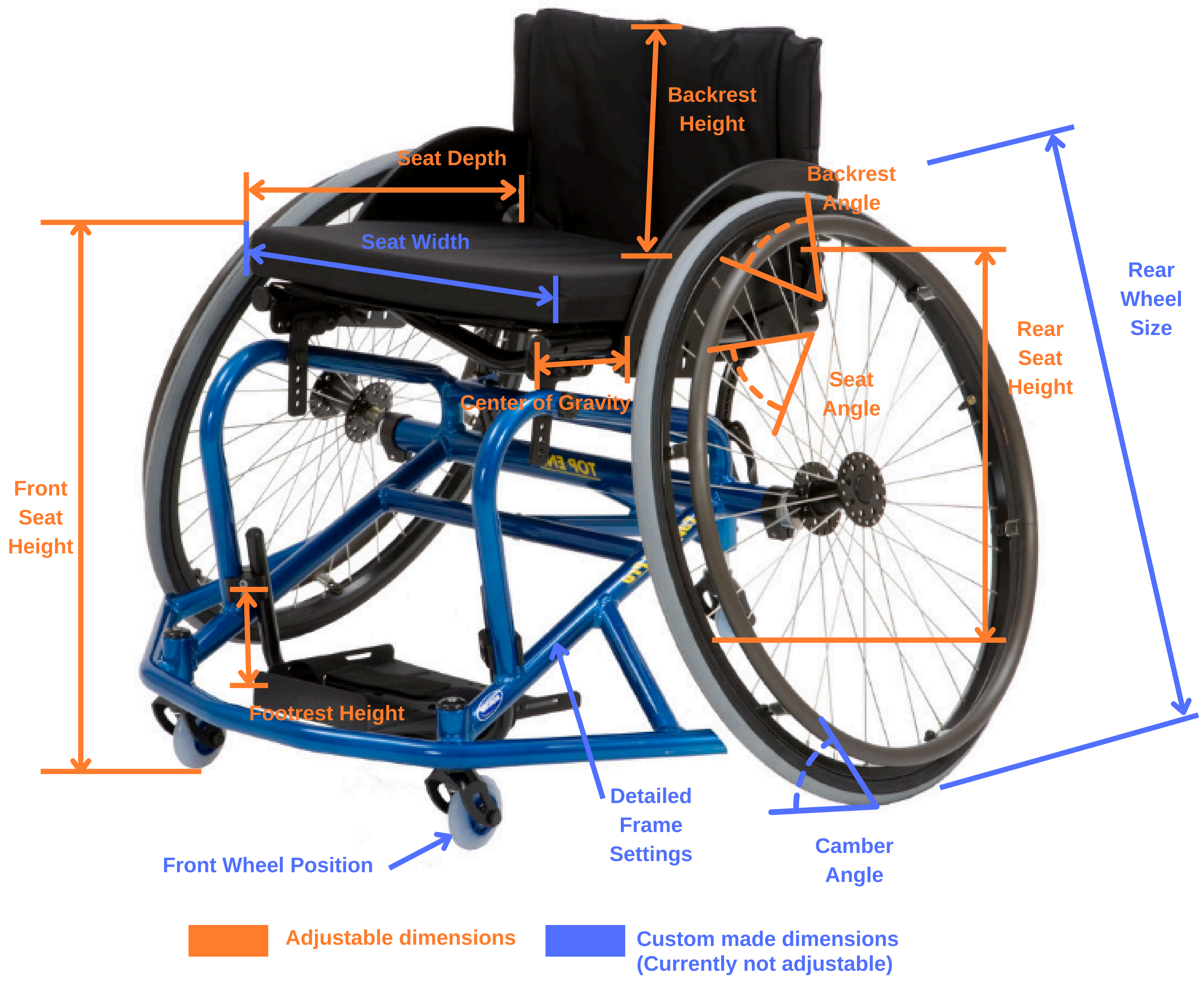


Figure 2.11 Schematic diagram of currently adjustable and custom made configuration dimensions

2.2 Literature Review

To match the insights from the current products analysis, this review was conducted aims to explore the significance and impacts of various configurations, while further identifying the gaps in the current adjustment functions of basketball wheelchairs.

This chapter reviews and analyzes relevant academic literature on sports wheelchair configuration as well as official rules from IWBF(International wheelchair basketball Federation) and WBC (Wheelchair Basketball Canada).

2.2.1 Wheelchair Configurations

This part of the review was conducted to go through basketball wheelchair configurations, figure out the importance of them and try to find opportunities for adjustability design.

The literature search on configurations (detailed information see Appendix A) was primarily compiled based on Scopus databases as well as supplemented by Google Scholar, searching for keywords constructed around wheelchair basketball, also using adaptive sports and wheelchair innovation. Other secondary terms (performance, wheel size, camber, configuration, mass) were used alone and in combination with keywords. Articles were included on the principle that they could be applied to the wheelchair basketball scenario, and the vast majority of the articles were specifically wheelchair basketball based, but some sports wheelchair content was also covered.

As is shown in Figure 2.12, the basketball wheelchair consists of multiple components, each of which can be customized according to user needs, which is why it is said to be highly customized. Traditional customized designs usually take months and extra human labor to be produced or maintained, prompting a growing interest in adjustable and semi-customizable solutions that offer both adaptability and efficiency.

De Groot et al. (2003) evaluated a wheelchair design from a Canadian company that permits a wide variety of adjustments, reducing the need for expensive customization. Its result shows that it was rated significantly superior concerning weight, maneuverability, rolling resistance and footrest stability but significantly inferior concerning height of the chair and backrest. This is consistent with the following insight, which suggest that additional adjustments in backrest or seat height is required in different player classifications situation.

1 Weight and seat position settings

In the domain of wheelchair basketball, weight and seat positioning are critical determinants of athletic performance, maneuverability, and safety.

Unlike standard wheelchairs, basketball wheelchairs are engineered with unique structural geometries and lightweight materials, such as aluminum alloys, to facilitate rapid acceleration, responsive turning, and overall agility on the court.

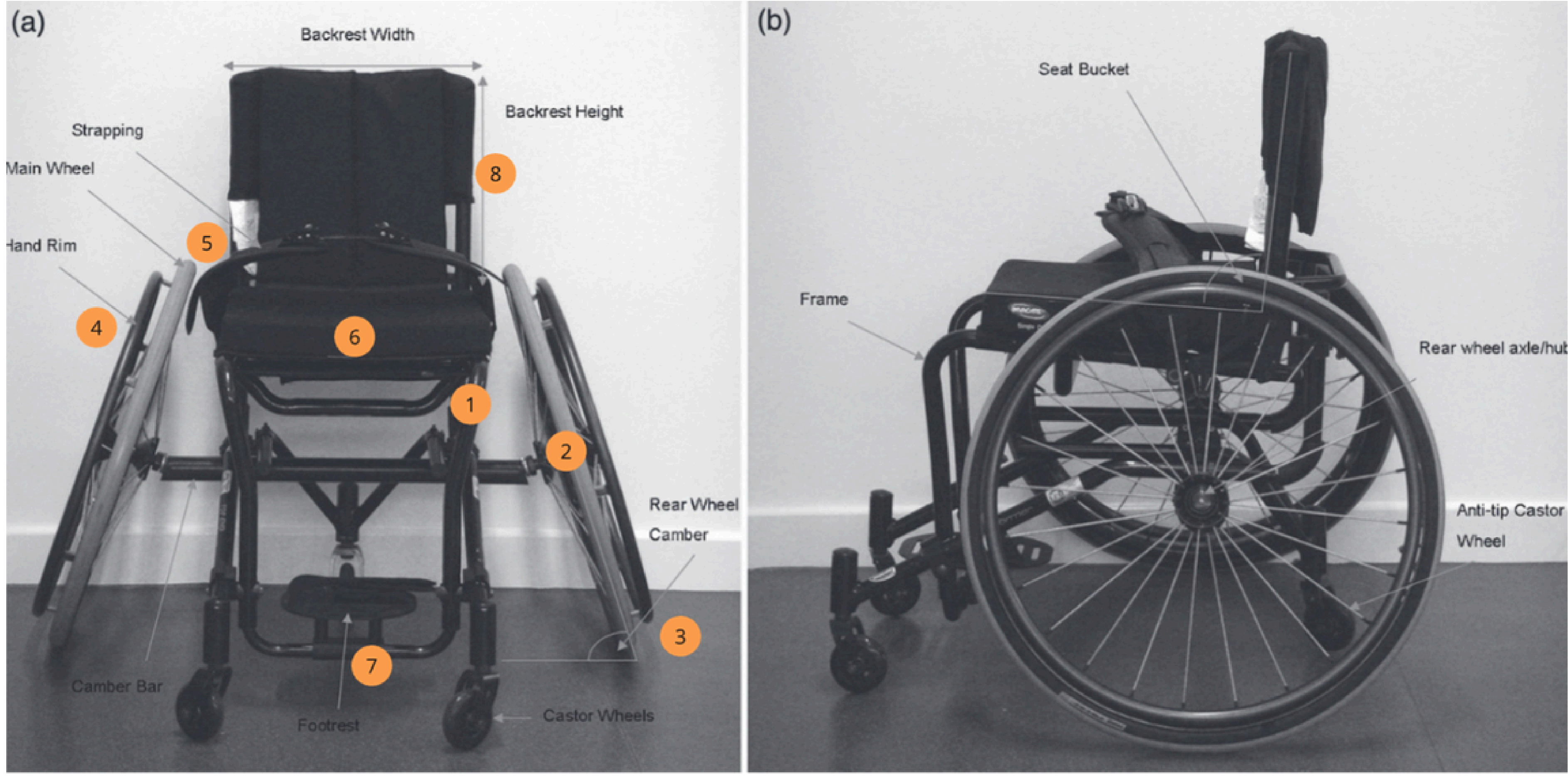


Figure 2.12 (a) Front on and (b) side on view of a sports wheelchair typically used for wheelchair basketball, illustrating different components of the wheelchair configuration

2.2 Literature Review

De Witte et al. (2020) tested on the total performance time on the wheelchair mobility performance which was significantly reduced when using a 7.5% lower seat height. Additional mass (7.5%) and glove use did not lead to changes in performance time. Meanwhile, according to Laferrier et al. (2012) light weight is a contributing factor for maximizing acceleration in the context of wheelchair sports, and Sagawa et al. (2010) also found no effects of additional mass (5kg) on sprint performance for sports wheelchair, but a little decrease in performance in the Stop-and-Go test. These findings collectively suggest that mass alone may not be the sole variable affecting general performance of the wheelchair; rather, mass distribution and center of gravity may interact with structural configurations to influence outcomes. While a lightweight frame remains a fundamental design criterion for basketball wheelchairs, the evidence indicates that **modest increases in weight may be tolerable**, provided they do not adversely affect dynamic tasks such as turning, stopping, or rapid directional shifts.

Additionally, an aluminum framed wheelchair design in the Netherland carried out by Berger et al. (2012) using the optimum moment of inertia in tubes by increasing the outer diameter of the aluminum tubes. This makes it possible to reduce wall-thickness and results in weight reduction, similar approach could be apply on other new designs on the wheelchair.

2 Rear wheel size and tyres

Research has examined the relationship between wheelchair wheel specifications and athletic performance. Mason et al. (2012) found that larger 0.65 m wheels improved maximal sprinting in elite players. Later, Mason et al. (2015) showed that wheel stiffness, tyre type, and orientation affect performance, with tubular tyres notably reducing rolling resistance and power demand compared to clinchers. The study concluded that tyre type is the most critical factor, while wheel stiffness may be more related to personal preference. Existing basketball wheelchairs have quick-release rear wheels, so changes in this aspect can be achieved by directly replacing the rear wheels. The balance of the wheelchair requires subsequent adjustment on the height of the anti-tipping wheel.

3 Camber angle

The camber angle of a basketball wheelchair refers to the angle at which the wheels are tilted inward at the top relative to the vertical axis when viewed from the front or back. Studies show that moderate camber angles (9°–15°) have little effect on energy expenditure or velocity, while higher camber (20°–24°) may improve mechanical efficiency but also increase tire deformation, suggesting no universal optimal angle exists. Instead, camber configuration should be tailored to individual needs and sport-specific demands (Faupin et al., 2008; Perdios et al., 2007; Mason et al., 2010). Also, the camber angle is determined by the rear wheel connection points that cannot be changed after customized manufacture.

4 Hand-rim size

The hand-rim is a device mounted on the outside of the rear wheel for the player to grasp and move the wheelchair. Research has shown that larger hand-rims can improve mobility performance but also increase physiological demand, with the optimal configuration likely depending on individual athlete strength (Van Der Woude et al., 1988; Veeger et al., 2017). Studies on hand-rim materials and shapes indicate only minor physiological differences, though cylindrical, rubber-coated hand-rims are generally preferred by users and remain the most common choice (Van Der Linden et al., 1996; Van Der Woude et al., 2003). Similarly, hand-rim size can be adjusted by replacing the rear wheels.

5 Straps

The straps on the seats are a necessary part of fastening the player to the wheelchair and also provide security. Typically there are two straps at the pelvis and knees, sometimes with additional straps at the feet and abdomen. Macchiarola et al. (2023) figured out that straps, as well as ensuring safety and preventing injuries, also improve the wheelchair basketball performance, stabilizing and implementing upper limb skills, without exposing players to excessive biomechanical stresses. As the flexible components on wheelchairs, they play an important role in bridging the gap between the user and the wheelchair, and **may also be used to improve the level of fit** in subsequent designs.

6 Seat width

As the basic dimensions of seat size fitting, seat sizes include width are usually the first to be settled in the customization process. According to Williamson and Cockram (2024), efficient energy transfer between the athlete and the wheelchair depends on a precise fit that minimizes unnecessary movement within the seat. **Secure contact between the pelvis and upper legs with the chair, which depends highly on seat width, enhances rotational control while optimized energy transfer reduces upper limb strain during propulsion and lowers spinal and pelvic loading during turning**, thereby decreasing the risk of musculoskeletal injury. Currently seat depth adjustment is achieved by added extension rods, while seat width can only be customized (the only example of ordinaryl wheelchair called PDG Eclipse see chapter 2.1).

7 Footrest

According to WBC (Wheelchair Basketball Canada), the foot plate should be high enough to sustain the weight of the lower legs, yet low enough to not raise the thighs off the seat. Ankles should be positioned directly under the knees or farther back towards the rear wheels.

8 Backrest height and angle

Also according to WBC, the backrest configuration varies by player classification (detailed description see Appendix C): lower-class players (e.g., 1.0) typically use slightly reclined backrests, while higher-class players use lower, more upright backrests to allow greater torso mobility.

2.2 Literature Review

2.2.2 Official Rules

In addition to the configurations above, some official regulations are available that set standards and boundaries for the ergonomics of basketball wheelchairs.

IWBF (International wheelchair basketball Federation) official rules set clear limits on the dimensions that wheelchairs can be designed to fit (shown on Figure 2.13). The seat height, measured with front castors in the forward driving position and the player removed, must not exceed: **63 cm for classification points 1.0 – 3.0 and 58 cm for classification points 3.5 – 4.5,** cushion included. Anti-tip castors positioned at the rear of the wheelchair must remain within the width defined by the inner edges of the two main wheels and not protrude beyond the vertical plane touching the rearmost points of the drive wheels with a maximum clearance of 2 cm from the playing surface.

Armrests and upper body supports affixed to the wheelchair must not extend beyond the player's natural body line, specifically the legs or torso when seated in a neutral position (Detailed information see Appendix B).

And According to the WBC guidelines, some key configurations like backrest, seat angle and height also varies by classification. In general, what can be concluded is that **There is no optimal configuration for everyone. The user's preference is closely related to personal habits, skills level, and player classification** which also represents mobility.

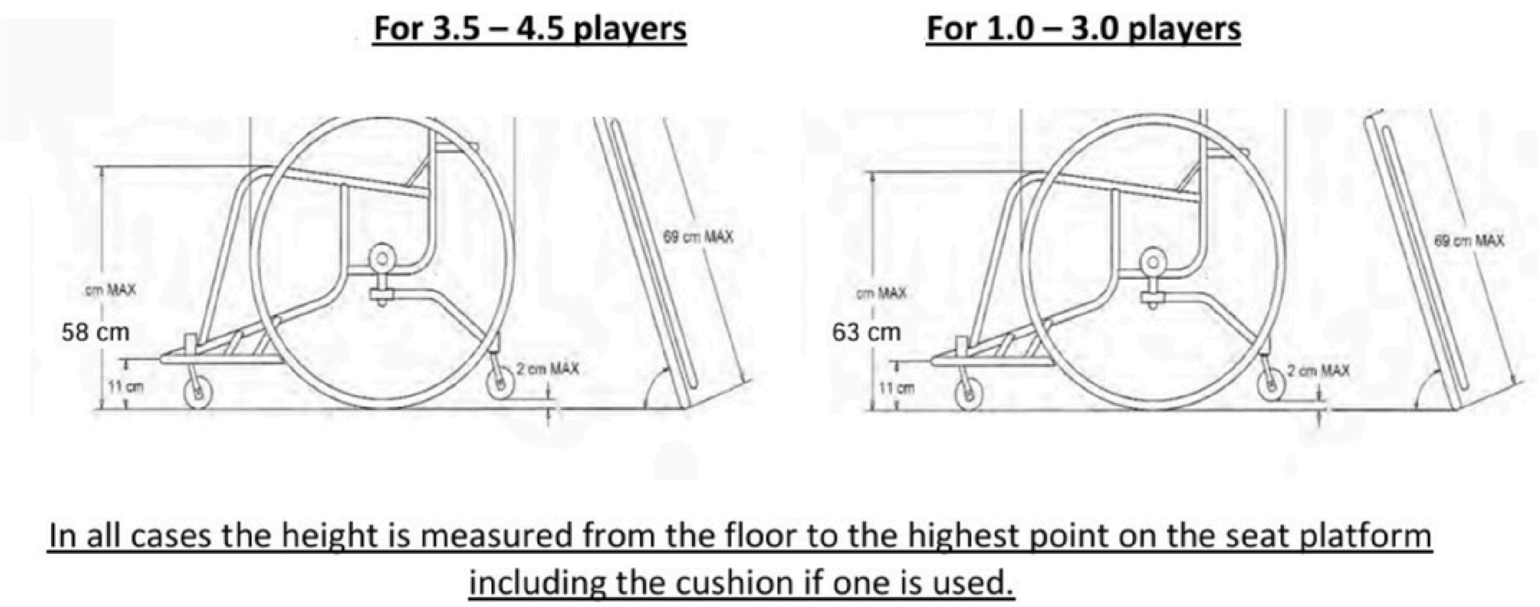


Figure 2.13 Seat height measurement

Takeaways

- **Optimal configuration settings appear to be highly individualized, with significant variation observed across different users.** In this case, determining universally effective design parameters sounds impossible without extended periods of user testing and adaptation.
- In terms of seat height, camber angle, backrest angle and height, the user's needs are highly related to their skill level and the degree of disability which reflected by the scores of classification.
- Among all the mentioned critical configurations above, **the camber angle and the seat width is currently not adjustable.** While these adjustments are currently recognized as beneficial to player experience and performance, the actual frequency and necessity of adjusting them in real-world contexts remain to be examined through field studies.
- There are clear restrictions of basketball wheelchair frame dimensions (chapter 2.2.2) that subsequent design and prototyping process must follow.

2.3 User Profile

To validate the issues identified in previous research and to broaden the research scope, I reached out to several wheelchair basketball clubs and organizations, eventually establishing contact with BS Leiden Rollers and conducting multiple visits. Insights from these interviews and observations were then used to refine the user scenarios and case.

2.3.1 User Interview

During the visits, unstructured interviews were conducted to gain preliminary insights into real-life wheelchair basketball context. Questions regarding background knowledge and their current pain points were carried out during the process. The coach and 2 of the players answered them and provided sufficient information.

Background information

Bs Leiden Rollers is a small wheelchair basketball club with around 20 people affiliated under the BS Leiden basketball team. There are close to 20 other clubs like this one in the Netherlands, so it is possible to estimate the number of regular players here to be around 400. The club regularly has 18 players, including recreational players, forming two teams of five that compete in two different leagues in the Netherlands. They have training session twice a week and compete on Saturday.

There are not only local players, but also participants from The Hague or Delft, as there are no local wheelchair basketball club or playing position in the local club.

Funding

However, they benefit from the policies of the municipality where they live to obtain funding for wheelchair equipment. Usually following Wet Maatschappenlijke ondersteuning (WMO), but also sometimes from Zorgverzekeringswet (Zvw) or Wet Langdurige Zorg (Wlz). Delft has the most favorable conditions for 100 percent coverage within certain limits, while others cover a certain percentage. Overall once they are able to meet the conditions, even recreational players when they have decided to get involved in the sport, **the cost they need to pay for a basketball wheelchair is limited to a few hundred euros at most.**

Wheelchair life cycle

Meanwhile, one of the players also mentioned that the cost of wheelchairs is not easily affordable for the government. The procedures take time, and the Government expects wheelchairs to be used for more than 10 years, **much longer than the normal 2 years warranty and 5 years lifespan expectancy** provided by the manufacturer. In this case **replacing an unfit wheelchair is almost impossible**, some players even have to tolerate their unfit wheelchair for years. For fast-growing teenagers, a properly fitted wheelchair may only remain perfect fit for 2–3 years, and changes in their playing style during growth may further shorten this period.

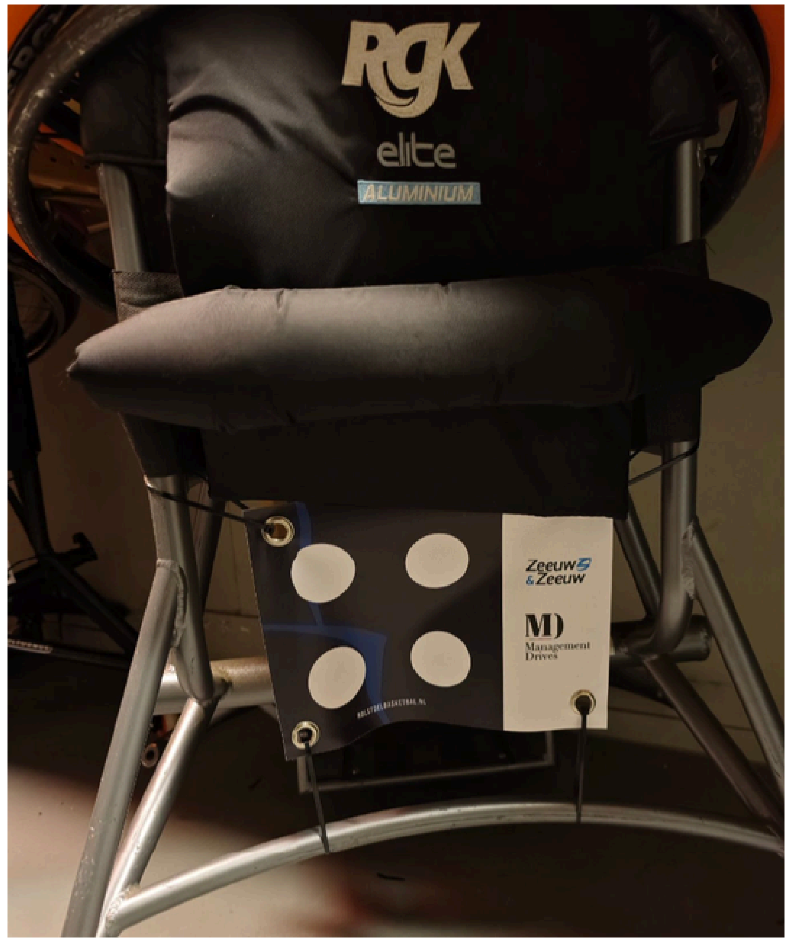


Figure 2.14 Used basketball wheelchairs stored in the club rest room

Fortunately, the club plays an quite essential role in this wheelchair basketball community. All players store their personal basketball wheelchair at the club (shown in Figure 2.14), and the **used wheelchairs also go back to the club to support new players** to come. This situation effectively reduces the need for new wheelchairs and prolongs their lifespan, the coach stated that 4 out of 10 people on the court having wheelchairs that have been used by others. They also explained that if any new comers or beginners wanted to participate, they could also use the club's wheelchair for the play.

Speaking of maintenance, the bearings on the rear wheels are the most frequently replaced part of the wheelchair, will be replaced about once a year, but the bearings are very cheap and simple to replace at home. The wheels can also be replaced individually in case of damage, but this also happens infrequently.

In general, their needs for wheelchairs can be summarized into this quotes:

‘They care about the price, but they care more about how the wheelchair fit their body and the quality of the wheelchair.’

- The Coach

‘The government wants the wheelchair to be used as long as possible, and we share our wheelchairs in the club.’

- One of the players

2.3.2 User Observation

Miscellaneous observations

Since all visits took place during BS Leiden Rollers' training sessions, valuable information and insights were obtained through close observation of the two teams' training processes and later confirmed with their coach and one of the players.

From the observation, the intensity of their daily training is significantly lower than the intensity of the competition (comparison and justification see Appendix E). In addition, the intensity of the team's twice-weekly, hour-and-a-half training sessions and the use of their wheelchairs by never leaving the court have resulted in **a relatively low rate of strain on the wheelchairs**. Here instances of wheelchair frames being damaged are extremely rare.

Observations of their movement patterns during training provided insights that corroborate previous research. Players with higher classification scores have more trunk movement, which means the backrest needs to be looser, while players with lower scores have relatively stay still trunks and require backrest support. Furthermore, players with higher scores tend to have a lower contact point with the hand rim, preferring to use both hands simultaneously rather than alternately, as is the case with lower-scoring players. Clearly, different classification scores dictate different wheelchair configuration requirements. (Detailed observation results see Appendix D)

Half of their wheelchairs are RGK wheelchairs, which are probably in the range of about €4,000 (according to previous market research), justifying that they value quality. And all of their rear wheels come from brand called Spinergy, really expensive up to €1000 but are of great quality. They commented that It is **better for them to use a high quality wheelchair for many years** than to buy a lot of short-lived wheelchairs, because the government will pay for them and it is not easy to get a new one.

Also they mentioned that they really prefer the adjustments and repairs to be done at home or at the club, because sending the wheelchair back to the company for adjustments and repairs takes a long time and keeps them from playing basketball for a long time as well, which is extremely inconvenient.

As shown in Figure 2.15, basketball wheelchairs are typically stored with the rear wheels removed and stacked on the seat to reduce the area they occupy. The interface between the rear wheels and the frame of the wheelchair has a quick release design.

This also led to the interesting fact that they could sit on the basketball wheelchair first and then install the rear wheels. This approach meant that the rear wheels could be separated from the wheelchair frame to a certain extent during the design process and then integrated at the end.

(a) (b)

Figure 2.15 Rear wheel connecting spot (a) and how rear wheels placed (b)

Observation regarding seat width

From detailed observations on their wheelchairs, it was noted that the new coming teenage player had additional side protection attached to his wheelchair (Figure 2.16). This was because **the seat width** of the other people's wheelchairs he was using was **too wide for him**, causing him to slide in his wheelchair, so the club added this structure as a temporary adjustment. While this offers some improvement, the sliding still happens during his movements.

Figure 2.16 Side guard addition (blue foam-like thing) for adjustment on a used wheelchair

Observing the seat widths of different players reveals that, excluding some players who don't fit properly, **the actual fitting seat width isn't equal to the hip width**. For some players, there's a visible gap between the sideguards and their thigh, while for others, the side fits tightly to the thigh, even squeezing it slightly.

Under the guidance and accompaniment of the coach, I tried out the wheelchairs available at the club and gained some insights. Regarding the issue of wheelchair seat width fitting, the wheelchair I tried still had about two fingers of space between my hips and the sideguards on both sides after I sat down. According to the coach, such a fit is generally acceptable for some users, while others need a tighter fit, or even a bit of squeezing. **The preference for seat width fit appears to vary among individuals, newcomers have no clear idea what kind of fitting level they want while more experienced players generally tend to favor a tighter fit.**

Also after practical experience, driving the wheelchair forward on the court puts a significant burden on the arm muscles, which highlights **the importance of the reach of the hand-rim on the rear wheel to the usability and mechanical efficiency** of the wheelchair. In this case, the coach and players also confirmed that design improvements on the seat require special attention to **maintaining a minimal gap between the sideguards and the rear wheels**.

2.3 User Profile

2.3.3 User pain points

In addition, some of the players also shared their own stories and pain point descriptions. Summarizing their personal stories and experiences, combined with information about current products, provides a broad user journey for the recreational wheelchair basketball player showing not only the developing process but also the pain points at different stage of participation.

Players with acquired disabilities find wheelchair basketball through referrals from friends, rehabilitation practitioners, clinics held by clubs and organizations or when seeking alternatives to sports activities that cannot be continued.

Players with congenital disabilities grew up participating in wheelchair basketball

Knowing the sport

Due to the high requirements of venues and equipment for this sport, it is not easy to find a platform to participate. Without the support of a platform or club, it is almost impossible to form a team.

First Experience

When they first go to a club to participate in wheelchair basketball, the wheelchairs they use are often provided by the club or free rental from organizations like Uniek Sporten who aim at promotes sports activities for people with disabilities.

1-2 months

The level of fit and comfort of their borrowed basketball wheelchair is usually low, but they all have to endure this unfit and discomfort for several months before they get their own wheelchairs.

Several participations later, players confirmed their interest in the sport and obtained support from the government for the purchase of personal wheelchairs in accordance with regulations such as the WMO.

Get their own wheelchair

However, grant applications and wheelchair manufacturing often take months, and players have to put up with unfit wheelchairs for a long time before individually customized wheelchairs are in place.

6-12 months

After playing for a long period of time players improve and get involved in the competition in the league, their playing habits and operating patterns change and the requirements for fitment change while becoming more demanding, often this is when players need new wheelchairs.

Compete in Competition

Even with a custom-made wheelchair, they may still feel unfit and discomfort due to changes in their physical body condition or improvement in their skill level. But it can take months to adjust or send the wheelchair back for maintenance.

For players who participate in official competition but still train part-time, they are still under the recreational framework because they are at a lower intensity and still play with recreational players.

?

International

A small number of players with both talent and opportunity will become fulltime player and involved in the international game, which can serve as the end of the recreational context and the beginning of professionalism.

Due to the strict disability level requirements for international competitions, some players are unable to enter the international stage because their disability level does not meet the requirements.

In recreational settings, it is clear that fitting requirements change more rapidly than wheelchair availability. In this case, wheelchair designed for long term fitting and adjustability may effectively address these pain points, thereby significantly improving the overall experience of players at the relevant stages.

2.3 User Profile

2.3.4 User Case

On my third visit, I was fortunate to have the opportunity to interview young player Johnny's mother and gain deeper insights into his situation. As a new player without his own wheelchair and a teenager undergoing rapid growth, he represented an ideal user profile for the functionality of an adjustable wheelchair.

Johnny

Age	14
Experience	6 months new player
Frequency	3 times a week
Living in	Delft near campus
Hobbies	Basketball & climbing

Johnny is the latest joiner to the club, he has ordered a wheelchair with the help of the municipality but over a month has gone by and production is still not complete so for now he is stuck with the club's used wheelchair. As he is very skinny, he slides around in the wheelchair when he plays and even with the added side protection it doesn't really fit.

He has a congenital disability, but is very active, not only joining wheelchair basketball but also participate in climbing for disabled. Besides his weekly training at Leiden, he also travels to Arnhem at weekends to participate in wheelchair basketball relevant activities. According to teammates and coaches, a fast growing teenager like him might need a new wheelchair in 2-3 years, but the replacement period government promised is about 4 years.

Key characteristics

- Players new to the community
- Start to play without their own wheelchair
- Get a used wheelchair from the community but unable to fit properly
- Rapidly changing level of skills and configuration preference, therefore need to alter their wheelchair settings many times during their training

Pain points

- Unable to fit in the used wheelchair **in many dimensions but particularly the seat width** (Figure 2.17)
- Unable to frequently adjust the wheelchair configurations accordingly to his body growing process

Opportunities

Opportunities for development lie particularly in enhancing wheelchair sharing within communities, thereby reducing the time and financial costs of purchasing a new wheelchair, increasing accessibility and resource efficiency.

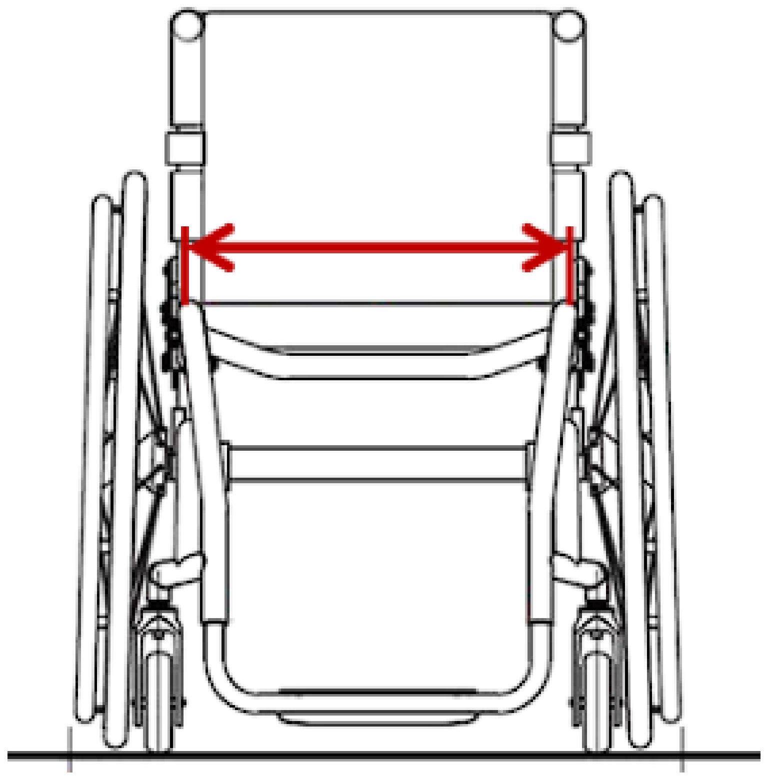


Figure 2.17 Seat width in wheelchair

2.4 List of requirements

Based on previous research and analysis, a list of requirements is summarized with the significant insights and conclusions as follows:

Category	Requirements	Origin
Basic features	• The size and range of adjustment of the wheelchair should comply to IWBF rules. Include seat height, anti-tip castors, backrests and legroom.	Chapter 2.1 Official rules
	• Wheelchairs must be strong and reliable enough to take the load of high-intensity competition maneuvers; ensure the safety of the user.	Chapter 2.3.2 User observation
	• The design of the wheelchair should be able to accommodate different configurations, such as wheel size; camber angle; seat dimensions.	Chapter 2.1 Market research
	• Added features and components must not disrupt basic functionality; shorten the lifespan; have negative impact on wheelchair performance such as propulsion efficiency.	Chapter 2.2 Wheelchair configurations Chapter 2.3.1 User interview
Adjustability feature	• The adjustability of the wheelchair should accommodate users' rapidly changing fitting needs. Adjust to fit one user's changing need; Adjust to fit different users.	Chapter 2.1 Market research Chapter 2.3 User profile
	• The adjustability of the wheelchair should integrate existing parameters such as seat height, seat depth, center of gravity and backrest angle, while incorporating new parameters such as seat width.	Chapter 2.1 Market research Chapter 2.3 User profile
	• The adjustability of the wheelchair should allow quick and convenient modifications without requiring return to the manufacturer or additional components.	Chapter 2.1 Market research Chapter 2.3.3 User pain points
Manufacture and costs	• The manufacturing process should be as short as possible to avoid long waiting time for players.	Chapter 2.3 User profile
	• The cost of the wheelchair must match the price positioning of the corresponding product range in the market to ensure commercial viability.	Chapter 2.1 Market research

Fierce competition on the court

03 Concept Design

3.1 Design Brief

The outcomes of the preceding research, analysis leads to a clearance of the design problem and the formulation of a comprehensive design brief.

The design challenge is to develop a basketball wheelchair in which the seat width can be **quickly adjusted and refitted multiple times throughout its lifespan**, maintaining a high level of fit for the changing physical conditions of a single user as well as for different users.

Current basketball wheelchairs on the market incorporate certain quick adjustment functions; however, **the seat width adjustment remains unaddressed** (Figure 3.1). In the previous research stage, across wheelchair customization, ergonomics, and **user needs, seat width has been consistently identified as a critical dimension**. Meanwhile, the camber angle adjustment range is relatively small and has not received that much attention from users.

Therefore, this design will focus on answering the question of **how to introduce quick seat width adjustment for recreational basketball wheelchairs**, while integrating existing adjustment dimensions and other factors linked to seat width as much as possible.

The adjustment process does not need to be rapid, but it should be feasible to carry out at home or in a sports club, without the need to return the wheelchair to the manufacturer. Some parts can be ordered from the manufacturer if necessary but must be able to be produced quickly.

Also the design will remain purely mechanical, without the use of electricity, to keep weight, accessibility and complexity manageable.

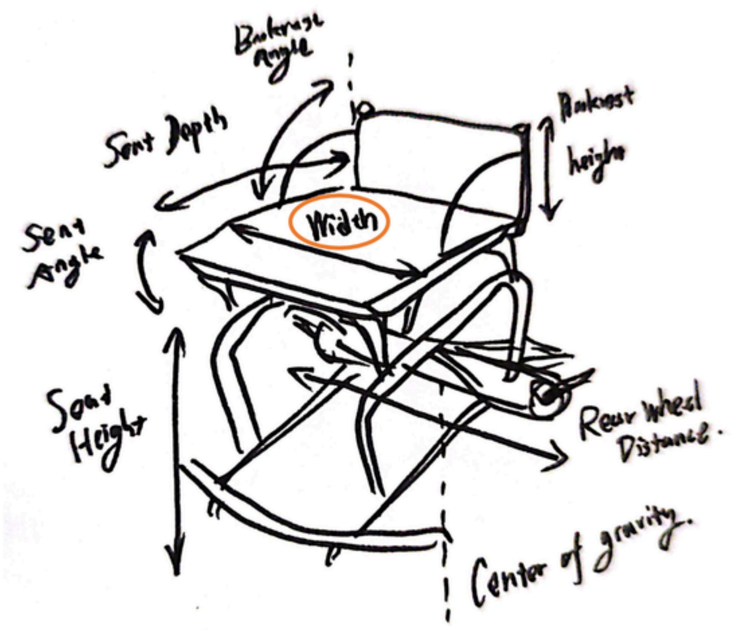


Figure 3.1 Dimensions need to be integrated in basketball wheelchair, especially addressing the seat width

Out of scope

- Adaptations for extreme body dimensions and special disability conditions may be out of scope.
- Remarkable improvement in level of comfort for cushion or backrest may be out of scope.
- Posture improvement for players with less mobility to avoid pain may not fit in the user scenarios.

Target user

Young Dutch wheelchair basketball players in recreational context, BS Leiden Rollers' players are typical of them.

3.2 Concept alternatives

3.2.1 Integration of adjustability

To incorporate seat width adjustment, **integrating other adjustable dimensions was necessary** during the concept development. Many of these dimensions inevitably interact with seat width adjustment, like seat angle and seat depth. At the same time, ensuring the feasibility of other dimensions is also an important prerequisite for achieving the goal of rapid wheelchair fitting. The Top End Pro wheelchair was chosen as the foundation for the design due to its widest range of adjustment options. The concept was centered around this wheelchair (Figure 3.2).

Multiple solutions for each dimension (shown in Figure 3.3 Morphological chart) were generated through brainstorming. These also included technologies and structures already used in existing RGK and Top End wheelchairs, as well as suggestions from players. Based on these sub-solutions, four different design concepts in two directions are combined and explored. The specific directions and concepts will be introduced later.

For one direction, given the interdependence among the 7 adjustable seat dimensions, it could be an efficient approach to **tailor the seat to individualized body contour**. In this case, all seat-related dimensions are adjusted at once, without clear boundaries.

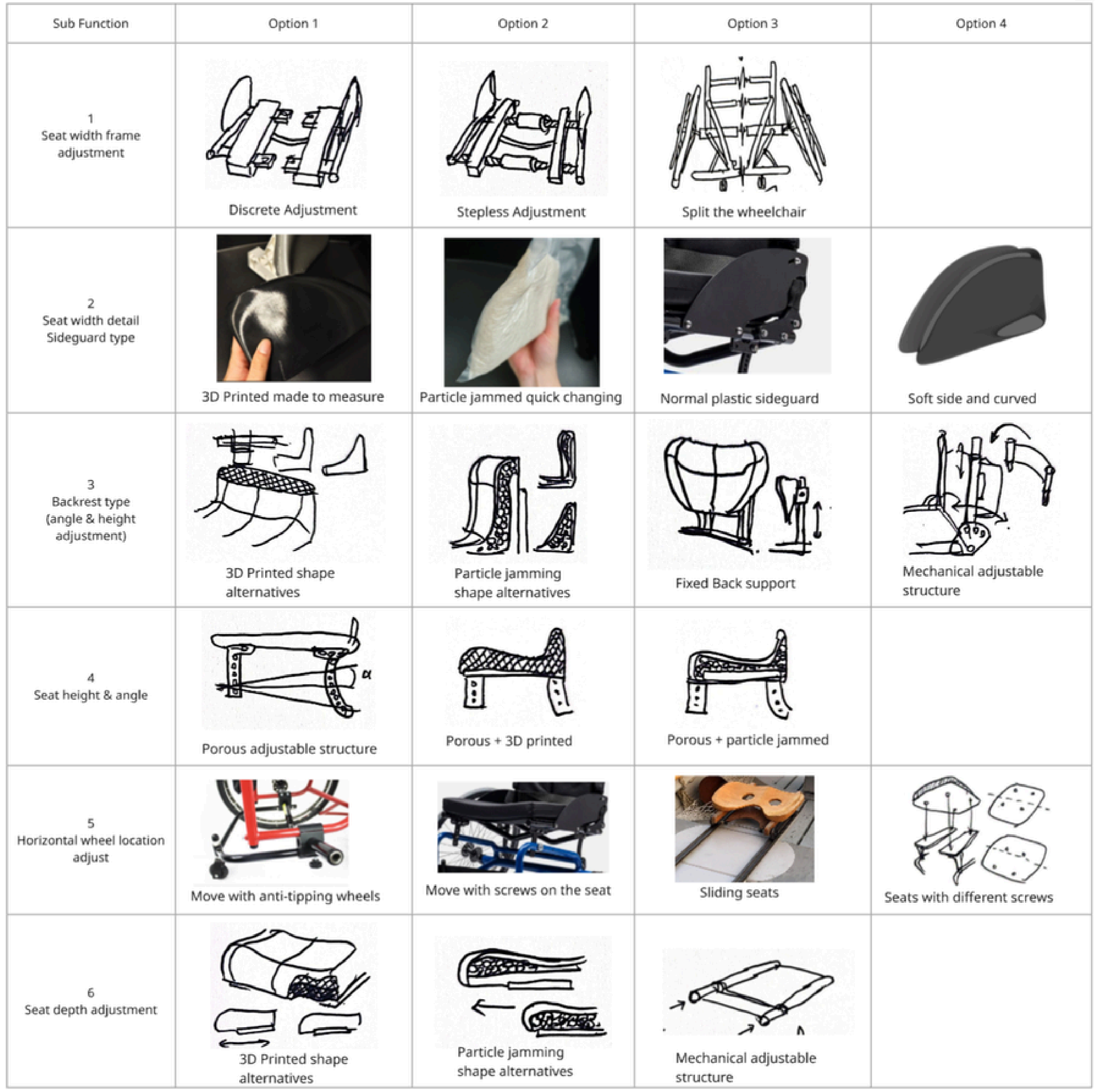
Figure 3.2 Positions of different adjustable dimensions shown on a existing wheelchair Top End Pro

This approach, widely applied in prosthetics or F1 racing seats design, could be designed to enable rapid customization by **introducing 3D printing or particle jamming technic**.

The additional advantage is that the individualized body contour can provide more sufficient supporting points around users' body, optimize energy transfer and stability. At the same time, the larger and more fitted contact surface allows pressure to be evenly distributed, avoiding pressure concentration problems and improving comfort. With cost and efficiency in control, this direction has the potential to replace existing mechanical structure adjustments.

And the other direction is **mechanical adjustment only**, trying to deal with adjustable dimensions one by one, adopting existing structure and introducing a seat width adjustment mechanism that does not interfere with other adjustment dimensions.

Focus more on the size than shape, may include universal body contour but no individualized body contour. The specific solution differs depending on whether the seats are separated or not.



Sub Function	Option 1	Option 2	Option 3	Option 4
1 Seat width frame adjustment	Discrete Adjustment	Stepless Adjustment	Split the wheelchair	
2 Seat width detail Sideguard type	3D Printed made to measure	Particle jammed quick changing	Normal plastic sideguard	Soft side and curved
3 Backrest type (angle & height adjustment)	3D Printed shape alternatives	Particle jamming shape alternatives	Fixed Back support	Mechanical adjustable structure
4 Seat height & angle	Porous adjustable structure	Porous + 3D printed	Porous + particle jammed	
5 Horizontal wheel location adjust	Move with anti-tipping wheels	Move with screws on the seat	Sliding seats	Seats with different screws
6 Seat depth adjustment	3D Printed shape alternatives	Particle jamming shape alternatives	Mechanical adjustable structure	

Figure 3.3 Morphological chart for solutions to different adjustable dimensions

3.2 Concept alternatives

3.2.2 Concept direction 1: Individualized body contour

3D printing based solution

The solution (see Figure 3.4) include a 3D printed seat, a lower frame and a connecting frame in between. The seat is customized to the user's body dimensions, with variable infill patterns controlling softness and stiffness for both comfort and support. It is mounted to the lower frame via a connecting frame that ensures sufficient structural strength while also permitting limited adjustments in both width and height. In this case, almost all seat-related dimensions are achieved by modifying the model of the 3D printed seat, also providing a individualized body contour.

When the existing seat becomes unfit or the user changes, a new custom 3D printed seat can be ordered to ensure optimal fit and comfort, allowing two users to share one wheelchair by replacing seats. However, this approach requires a dedicated service system for measurement and printing, and faces challenges of high complexity and difficulty in maintaining correct wheel and hand-rim positions when seat width changes.

Sub Function	Option 1	Option 2	Option 3	Option 4
1 Seat width frame adjustment	Discrete Adjustment	Stepless Adjustment	Split the wheelchair	
2 Seat width detail Sideguard type	3D Printed made to measure	Particle jammed quick changing	Normal plastic sideguard	Soft side and curved
3 Backrest type (angle & height adjustment)	3D Printed shape alternatives	Particle jamming shape alternatives	Fixed Back support	Mechanical adjustable structure
4 Seat height & angle	Porous adjustable structure	Porous + 3D printed	Porous + particle jammed	
5 Horizontal wheel location adjust	Move with anti-tipping wheels	Move with screws on the seat	Sliding seats	Seats with different screws
6 Seat depth adjustment	3D Printed shape alternatives	Particle jamming shape alternatives	Mechanical adjustable structure	

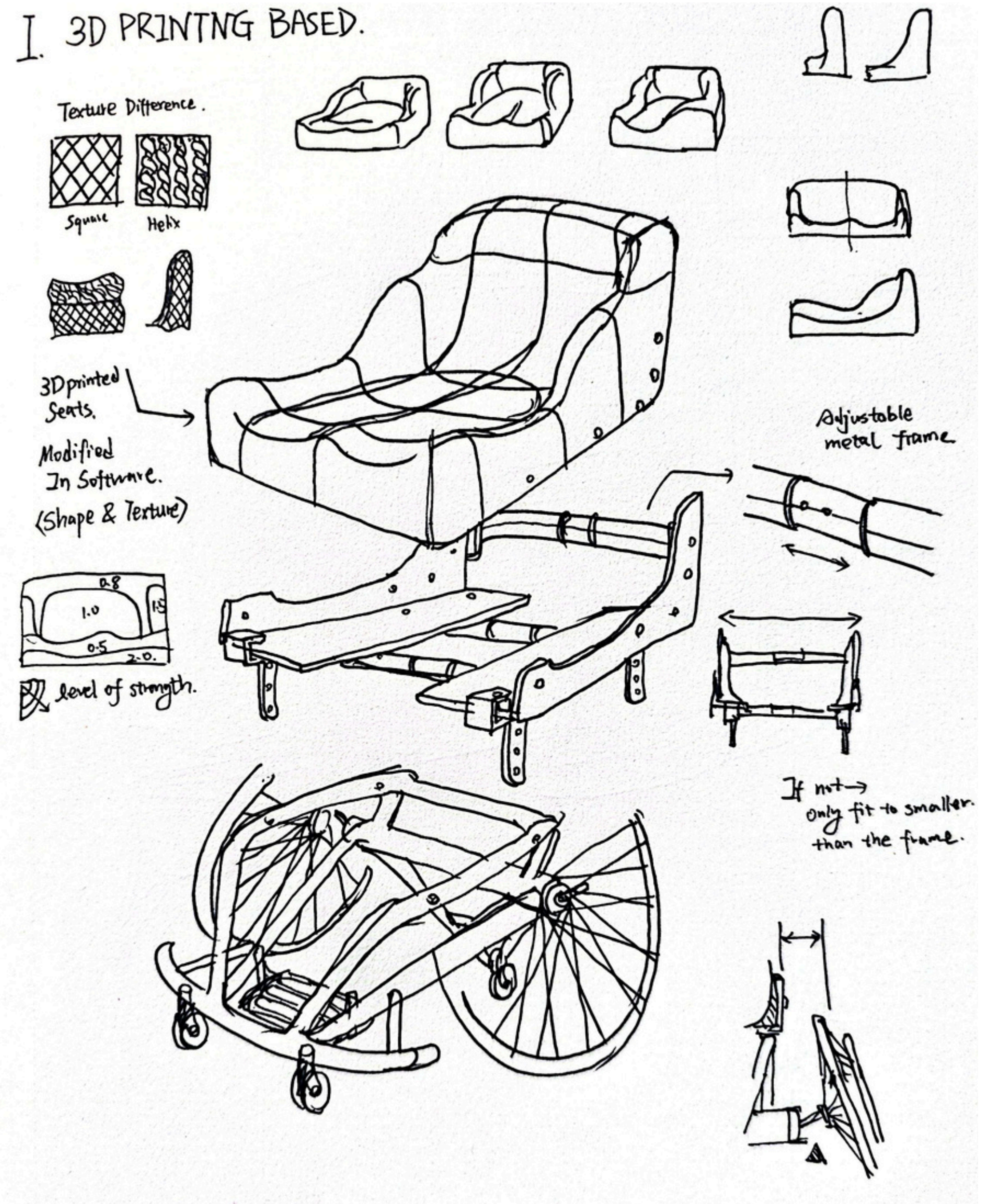


Figure 3.4 Morphological chart and sketches of 3D printing based solution

3.2.2 Concept direction 1: Individualized body contour

Particle jamming based solution

The structure of this solution is similar to the previous one, but the 3D printed seats are replaced with seats (see Figure 3.5) with integrated particle jamming technology. Particle jamming creates flexible, shape-adaptive interfaces by controlling stiffness, exploiting the transition of particulate media from fluid-like under excess air to solid-like under vacuum compaction (further information see Appendix G). The idea is to place a film-covered layer of particles between the wheelchair cushion and the frame of the seat, and to change the morphology of these particles through particle jamming to achieve different adaptations.

The program also requires convenient devices for rapid filling and evacuation of gases, as well as interfaces for injecting additional particles. The advantage is that it could adjust instantly without any waiting and without the need for additional customization of other modules, but controlling particle jamming applied to the seat is not easy, and its strength to support the high-intensity collision of wheelchair basketball is unknown. In addition it can only support a small range of adjustment and cannot be widened outward.

Sub Function	Option 1	Option 2	Option 3	Option 4
1 Seat width frame adjustment	Discrete Adjustment	Stepless Adjustment	Split the wheelchair	
2 Seat width detail Sideguard type	3D Printed made to measure	Particle jammed quick changing	Normal plastic sideguard	Soft side and curved
3 Backrest type (angle & height adjustment)	3D Printed shape alternatives	Particle jamming shape alternatives	Fixed Back support	Mechanical adjustable structure
4 Seat height & angle	Porous adjustable structure	Porous + 3D printed	Porous + particle jammed	
5 Horizontal wheel location adjust	Move with anti-tipping wheels	Move with screws on the seat	Sliding seats	Seats with different screws
6 Seat depth adjustment	3D Printed shape alternatives	Particle jamming shape alternatives	Mechanical adjustable structure	

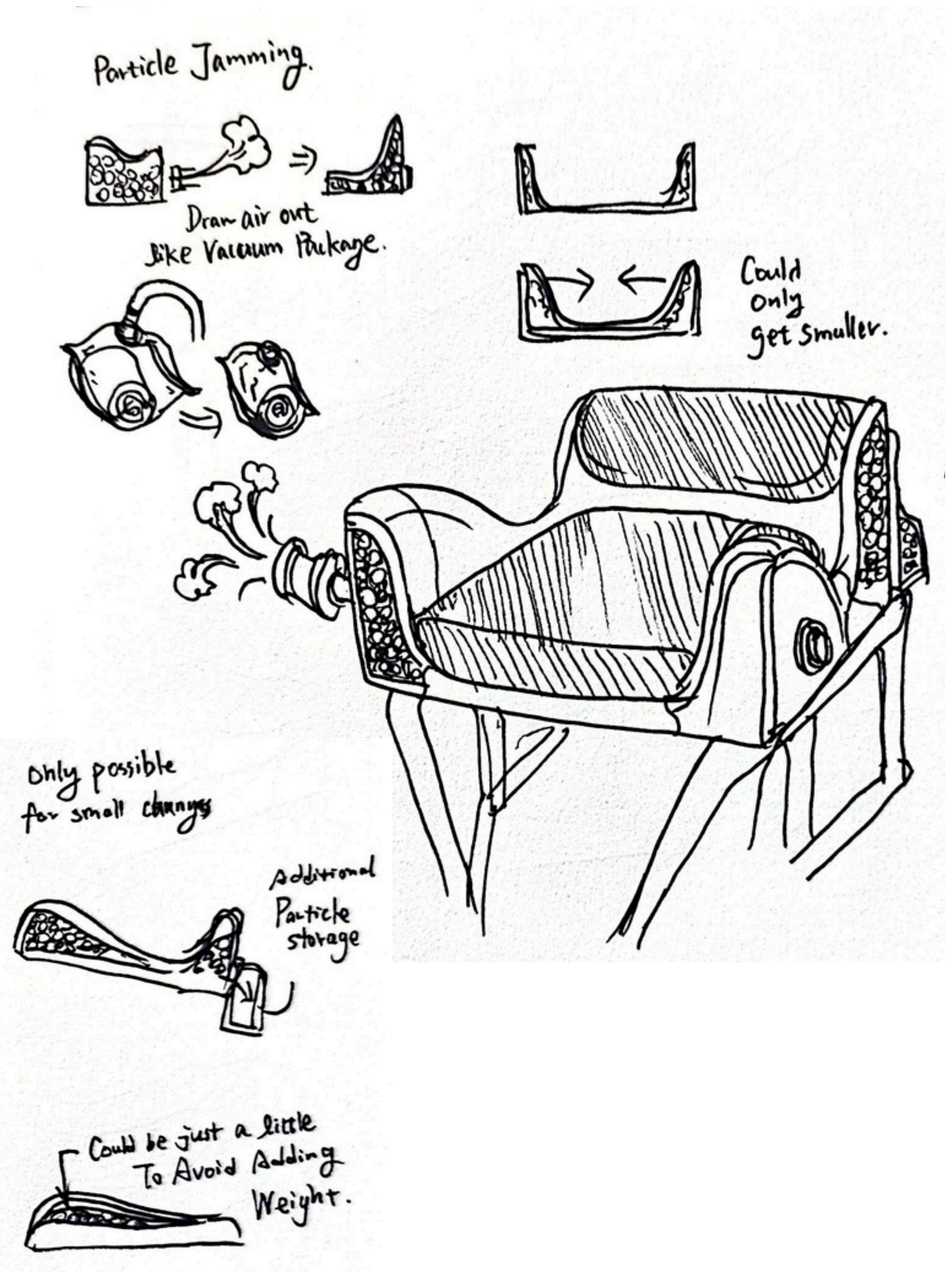


Figure 3.5 Morphological chart and sketches of particle jamming based solution

3.2.3 Concept direction 2: Mechanical adjustment only

Frame into pieces solution

The solution (see Figure 3.6) is a mechanical structured design that completely breaks down the wheelchair frame into several modules. The frame of the wheelchair is divided into four pieces, front to back, left to right, which are connected by a stretchable bar structure, thus realizing the adjustability of the seat width and depth without affecting the relative position of the rear wheels and the hand rim.

However, seat connections, cushions, and backrests still require customization or size-specific purchases.

The overall strength and performance depend on the connecting stretchable bar, but multiple connection sections raise concerns about stability, and conflicts may arise between lateral and longitudinal adjustment structures. Moreover, achieving front-to-back expansion requires a parallel frame construction, which is incompatible with tilt-angle seats. And most importantly, it cannot be adjusted while sitting, might require multiple attempts to achieve high level fitting.

Sub Function	Option 1	Option 2	Option 3	Option 4
1 Seat width frame adjustment	Discrete Adjustment	Stepless Adjustment	Split the wheelchair	
2 Seat width detail Sideguard type	3D Printed made to measure	Particle jammed quick changing	Normal plastic sideguard	Soft side and curved
3 Backrest type (angle & height adjustment)	3D Printed shape alternatives	Particle jamming shape alternatives	Fixed Back support	Mechanical adjustable structure
4 Seat height & angle	Porous adjustable structure	Porous + 3D printed	Porous + particle jammed	
5 Horizontal wheel location adjust	Move with anti-tipping wheels	Move with screws on the seat	Sliding seats	Seats with different screws
6 Seat depth adjustment	3D Printed shape alternatives	Particle jamming shape alternatives	Mechanical adjustable structure	

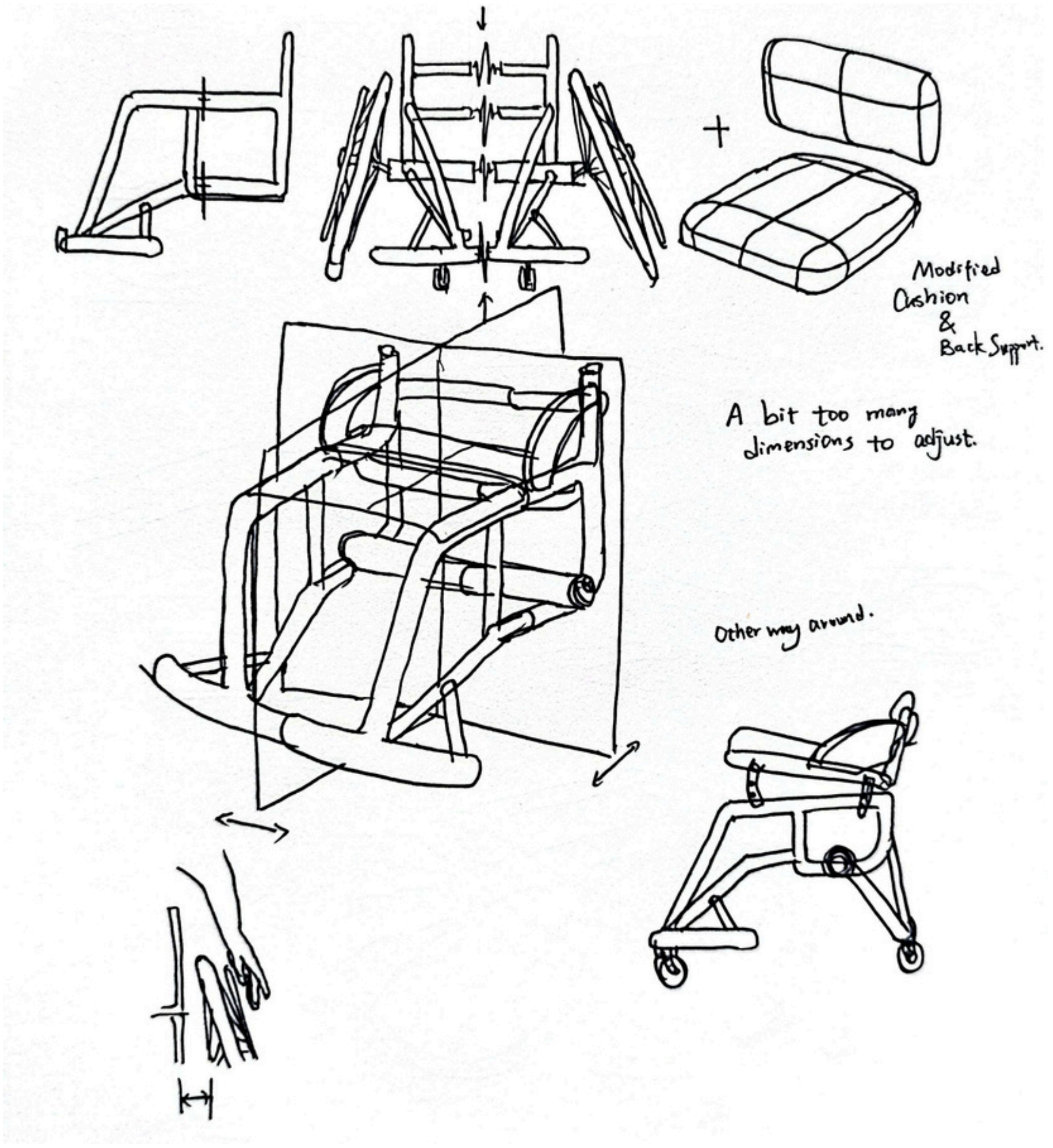


Figure 3.6 Morphological chart and sketches of frame into pieces solution

3.2.3 Concept direction 2: Mechanical adjustment only

Adjustable seat frame solution

The structure of this solution (see Figure 3.8) is similar to the connecting frame of the 3D printing solution, but leave all the adjustment to be achieved by mechanical structure. The frame of the wheelchair is divided into two parts, a seat that adjust and a lower frame that almost don't change. Since there is no other structural buffer on top of the seat, the width adjustment structure should be stepless and equipped with a sideguard with a inward curvature and elasticity to provide better comfort during moving and hitting situations. Due to the fixed lower frame and to prevent the seat from incorporating excessive adjustment mechanisms, the integrated anti-tipping and rear wheel system from RGK Club Sport is adopted to enable center of gravity adjustment. And most of the adjustment mechanisms on the seat were adopted from Top End Pro.

The core of this design is the stepless seat width adjustment mechanism, which must be well-designed to ensure functionality and strength. The seat cushion and backrest also need to be customized or properly designed to accommodate different widths.

Sub Function	Option 1	Option 2	Option 3	Option 4
1 Seat width frame adjustment	Discrete Adjustment	Stepless Adjustment	Split the wheelchair	
2 Seat width detail Sideguard type	3D Printed made to measure	Particle jammed quick changing	Normal plastic sideguard	Soft side and curved
3 Backrest type (angle & height adjustment)	3D Printed shape alternatives	Particle jamming shape alternatives	Fixed Back support	Mechanical adjustable structure
4 Seat height & angle	Porous adjustable structure	Porous + 3D printed	Porous + particle jammed	
5 Horizontal wheel location adjust	Move with anti-tipping wheels	Move with screws on the seat	Sliding seats	Seats with different screws
6 Seat depth adjustment	3D Printed shape alternatives	Particle jamming shape alternatives	Mechanical adjustable structure	

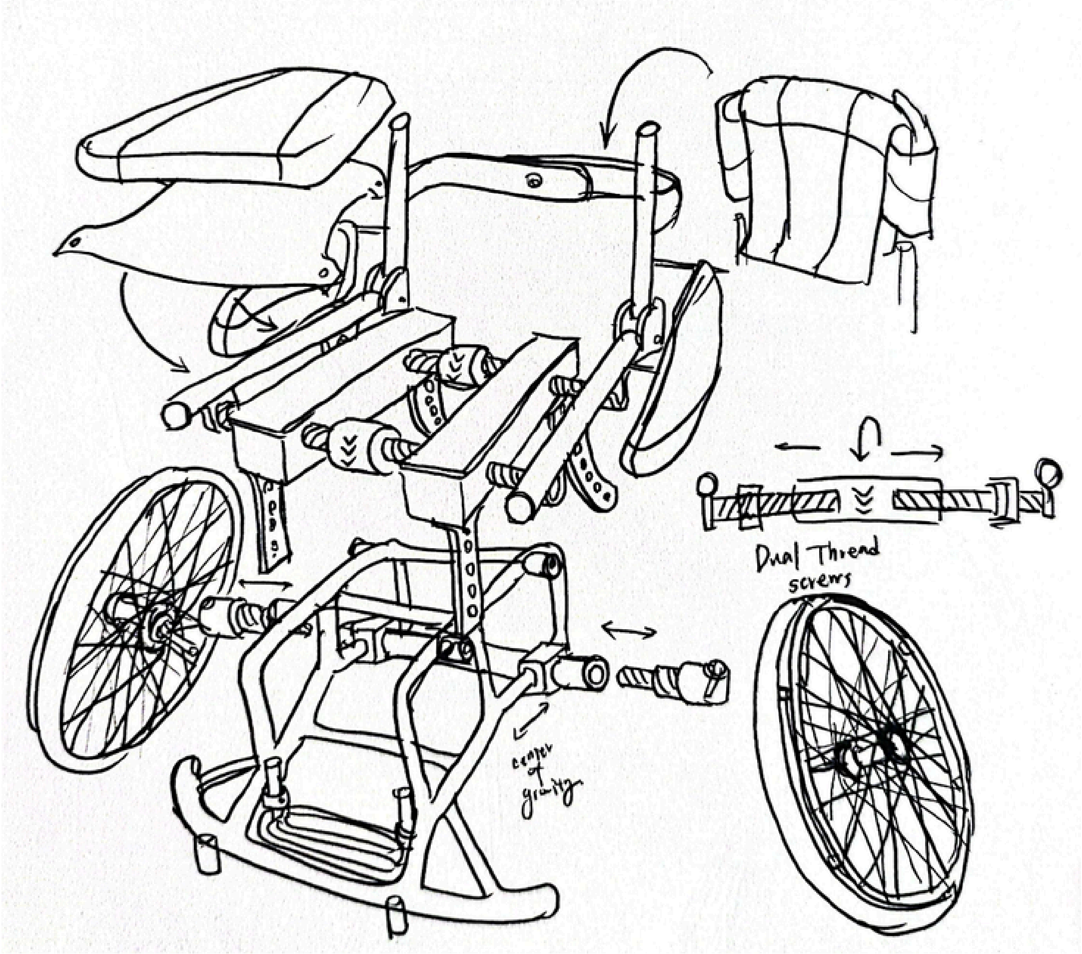


Figure 3.7 Morphological chart and sketches of adjustable seat frame solution

3.3 Further exploration on alternatives

3.3.1 Technology exploration

Is individualized body contour necessary?

To evaluate the concept, the first question to be answered is whether the individualized body contour is necessary.

Several models were printed to justify the infill patterns functionality mentioned in the concept design phase. A pair of 1:2 sideguard (see Figure 3.8) was printed in TPU with a bit lower density gyroid on the inner side and higher density cubic outside. The sideguard itself provides a very comfortable experience, but during the production phase, it was also realized that **3D printing the entire seat is difficult in terms of printer, time, materials and post-processing** (detailed exploration see Appendix H).

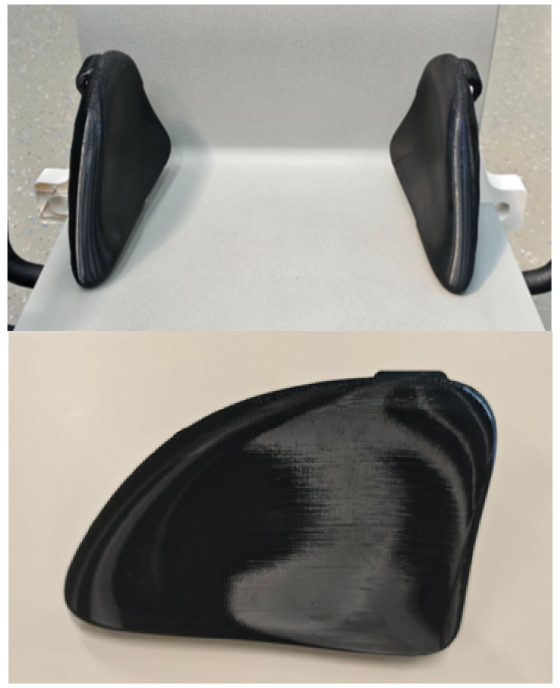


Figure 3.8 Sideguard test model printed in TPU

And then the particle jamming solution was tested with vacuum bags and rice. As shown in the Figure 3.9, the user sits between the bag-based-sideguards filled with rice, adjusts his posture and squeezes the bags, and the bags change shape and are gradually drawn into a vacuum. During the test, the particle jamming's **ability to conform to body contours was suboptimal, and its actual strength was concerning**. In addition, the suction device still presents design and assembly challenges (detailed exploration see Appendix I).

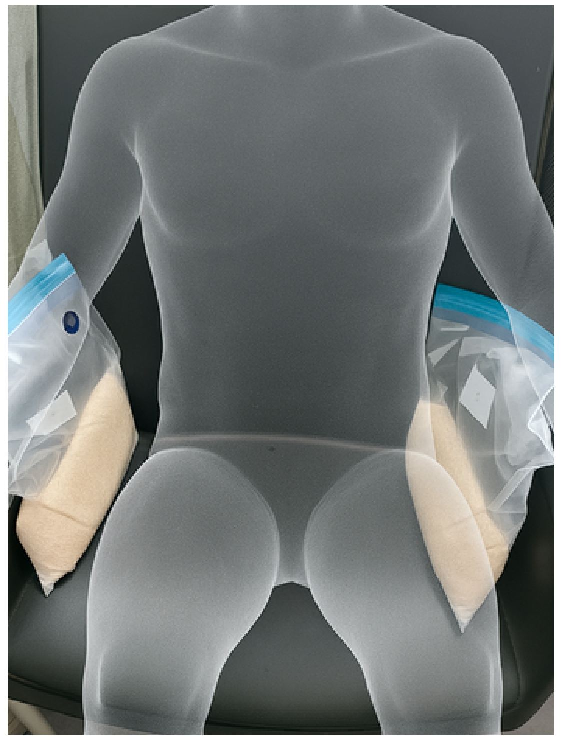


Figure 3.9 User testing bag-based-sideguards filled with rice

3.3.2 Seat adjustment user test

What's the key of seat width fitting?

To further evaluate the value of individualized body contour and explore the key factors in seat width adjustment, an test using a simplified device (Figure 3.10) was conducted with the help of 3 participants at IDE.

Test set up

A set of wooden strips are connected to a continuously punched wooden board by iron connectors, and their position can be changed by connecting to different holes. At the sideguard position, models 3D printed with TPU and wooden boards were installed for testing. Different positions of the wooden boards can simulate different sideguard sizes (see Figure 3.11 & 3.12). They tried adjusting the width of the TPU model and wooden boards of different positions to their own size, and rated their comfort levels based on a 1-7 Likert scale when they were stationary, moving left and right, hitting something and being pushed from the back.

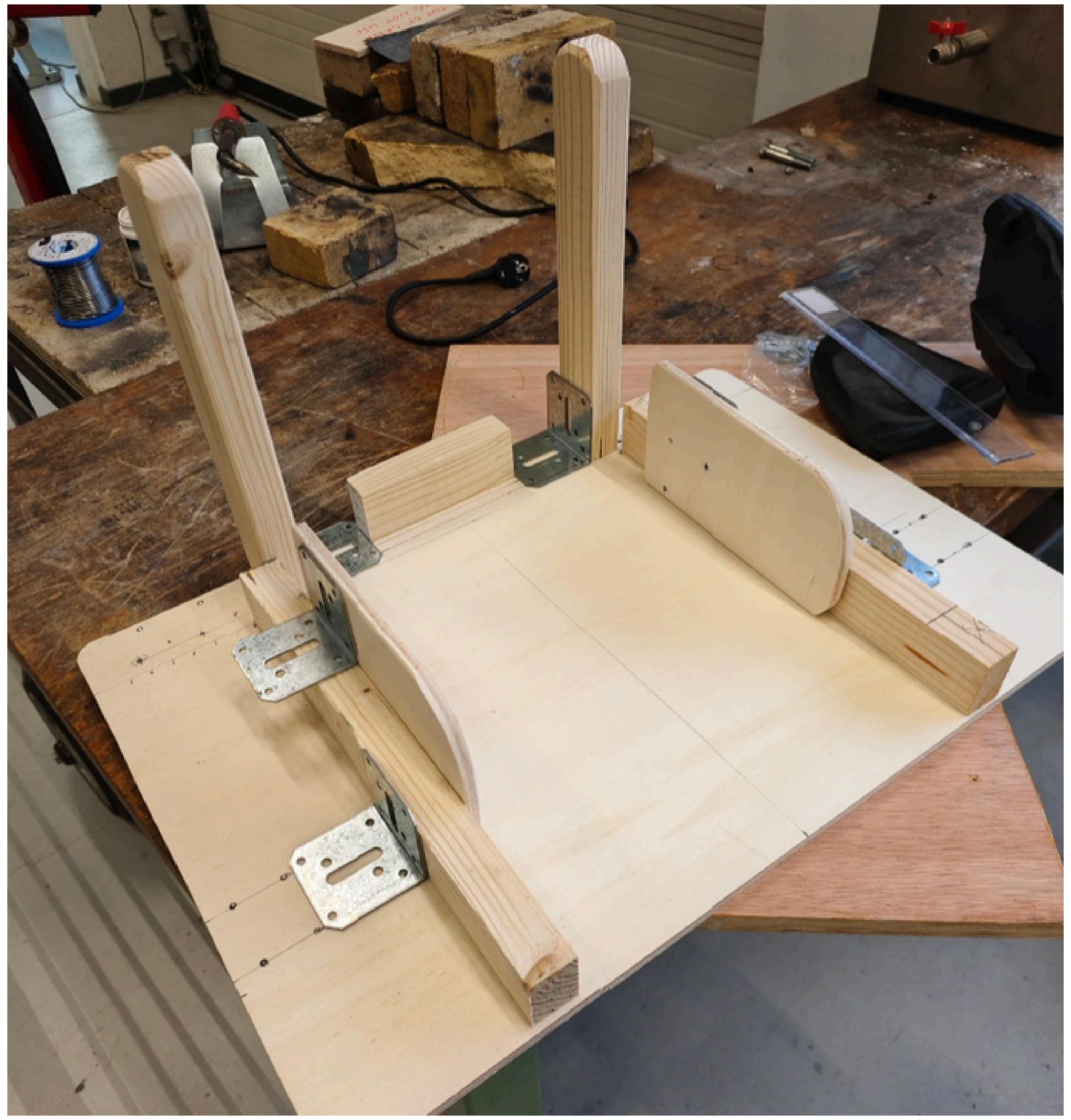


Figure 3.10 Basic settings for the test

Figure 3.11 TPU 3D printed sideguards and wooden boards sideguards installed

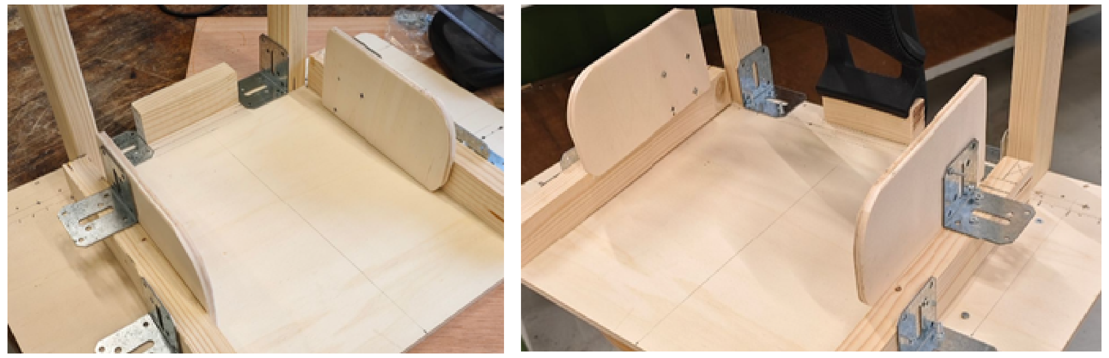


Figure 3.12 Different wooden board positions that represent small and large sideguards

3.3 Further exploration on alternatives

Process and results

The results of the experiment (Figure 3.13 & 3.14) showed that participants all preferred the TPU model and wooden board connected in the upper position, which represents the larger sideguard. Two of the three people agreed that the TPU model was more comfortable due to its relatively flexible contact, while the remaining one thought that under sufficiently close contact, **there was not much difference between the TPU model and the wooden board**. Due to the large individual differences among participants, the curved TPU model cannot adapt to everyone's body curves. Therefore, except for its outstanding performance during hitting, it is sometimes not much different from the wooden board in other scenarios. Also, due to printer and time limitations, the TPU model was printed in a smaller size than real life, and participants generally believed that a larger TPU sideguard would have better comfort performance.

Since there are certain intervals between the holes in the wooden board, and the thickness of the TPU model is not exactly equal to the intervals, the distance between the model and different participants is also different, and those with a better fit will score higher in the overall comfort. At the same time, some people have closer contact with the wooden board than the TPU model, and in this case, they will feel that the overall comfort of the wooden board is higher than that of the TPU material.

Due to limited conditions, there were no wheelchair users among the participants, and all were able-bodied people. However, this result is consistent with the information obtained from interviews with wheelchair basketball users that comfort is related to seat width fitting level.

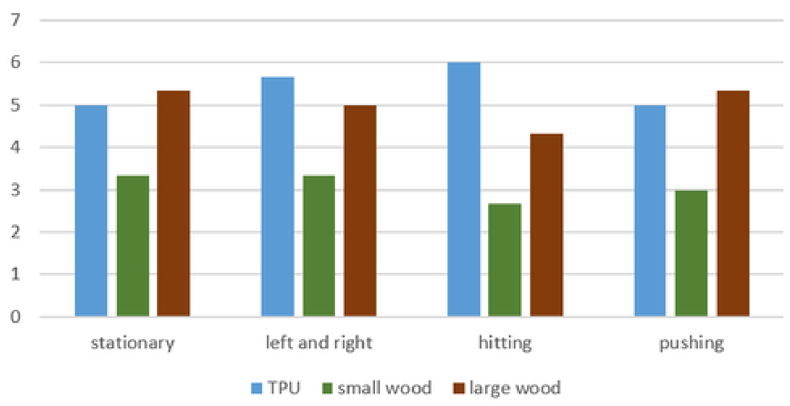


Figure 3.13 The average scores of the 3 participants on each motion

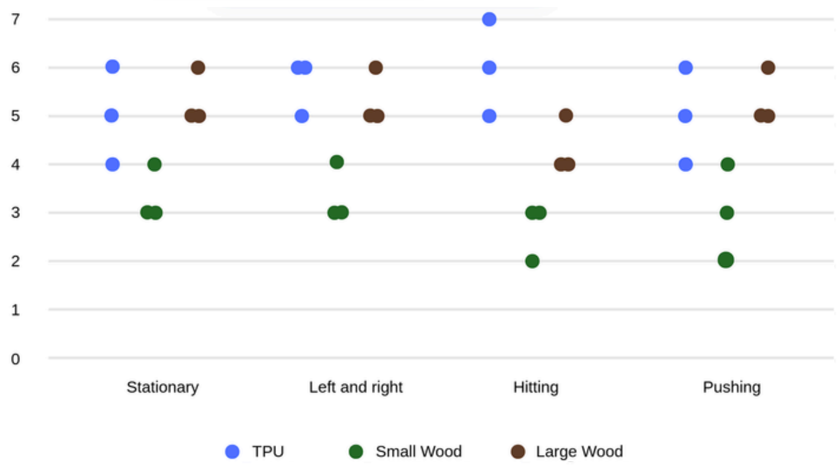


Figure 3.14 The scores of the 3 participants on each motion, Vertical axis shows the scores, horizontal axis shows the type of motion.

Figure 3.15 TPU model compared with the wood plate

In addition, the test also briefly compared the fixed backrest and the backrest that moves with the seat width in the morphological chart, and to a certain extent verified the choice of the backrest being the same width as the seat. (see the Appendix J for details)

As shown in Figure 3.15, the TPU model and the wood plate were not built in the same shape and thickness. Overall, the curved and flexible material of the sideguard improve comfort, but it is also limited by individual differences and situations. **The perfectly fitting seat width becomes the most important factor affecting comfort and fit. Despite this, participants generally noted that while fitting position is important, incorporating curvature or elasticity is perceived as beneficial.**

Takeaways

- **An individualized body contour is beneficial but not among the top priorities.** It's **not as important as a perfectly fitted seat width, but it costs more and takes more time.** Nevertheless, a curved or a bit elastic sideguard may still be an option to improve perceived comfort.
- Since human body dimensions are continuous rather than discrete, **stepless adjustment is essential to achieve an optimal fi**t. The adequacy of this fit is ultimately determined by the user's direct physical sensation. Moreover, **only when adjustments can be made while seated** can both efficiency and functionality of the adjustment be maximized.

3.4 Concept choice

According to the list of requirement and the results of the exploration test, the criteria used for the assessment of the 4 concepts were reliability, level of comfort, level of fit, adjustment simplicity, range of adjustment, interaction with other configurations as well as cost and manufacture speed (Figure 3.16).

The 3D printing based solution has shown some minor yet notable advantages in comfort and fit, but it cannot be adjusted in real time, and the additional measurement and production processes also severely limit the prospects of this solution. Furthermore, previous research has confirmed that an perfect fit doesn't equate to exact body measurements, as users have different skill levels and personal preferences. This means it will take a long time to determine exactly what firmness and size users prefer.

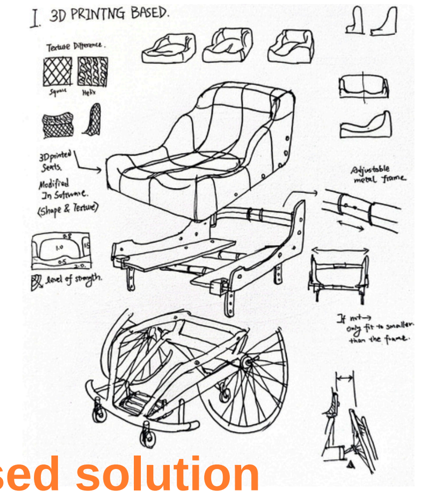
The particle jamming based solution‘s performance in terms of reliability, comfort and adaptability is inferior to the previous solution, but the real-time particle jamming provides a very quick and easy adjustment function. Unfortunately, the range of its adjustment is the most limited, and the materials and airtightness requirements are relatively high.

Also as mentioned before (chapter 2.3.2), **the actual fitting seat width wasn't equal to the hip width**, because players have different preference on the gap between their hip and the sideguards. Experienced players may have an intuitive understanding of the appropriate gap to they want to maintain; however, achieving an optimal adjustment remains challenging in practice. For newcomers who have just started playing for a month or two, it still takes time for them to figure out their preference, and simply copying individual body contour doesn't actually work. In general, **the shape of the individualized body contour is valuable but also flawed and not a necessary condition**, making the time and material cost of extending the concept in this direction not worthwhile. However, some detailed designs for a **universal body contour can remain effective** when costs are reasonable and comfort gains are meaningful.

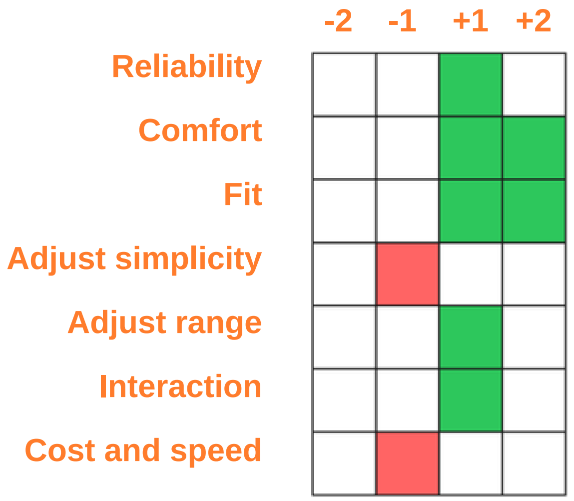
The frame into pieces solution has a relatively balanced performance in terms of fit and comfort, but splitting the entire wheelchair frame affects the structural strength, and the complex structure makes it relatively hard to be produced and adjusted quickly.

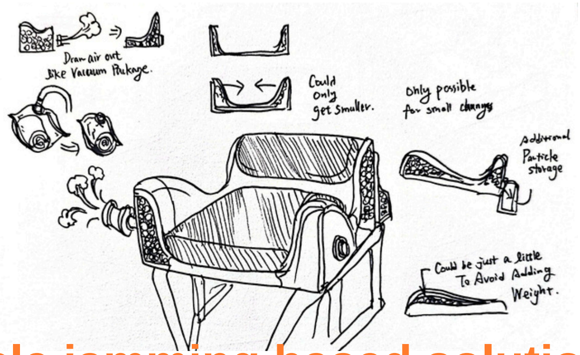
The adjustable seat frame solution generally performs well across multiple aspects. While the adjustment structure may add weight, previous studies have shown that modest weight increase is tolerable. The adjustment is concentrated in the seat and the lower frame remains unchanged, which makes it easier to adjust. Although it does not follow the human body contour, the stepless seat width adjustment is sufficient to achieve a perfect fit.

As a result, **the adjustable seat frame solution got the highest score, and was chosen to be further developed in this study.**

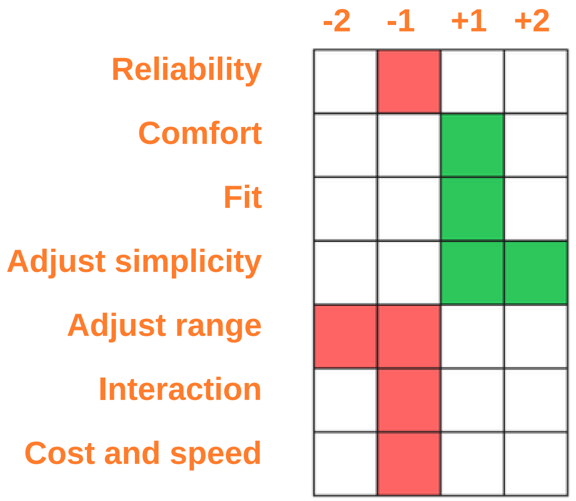


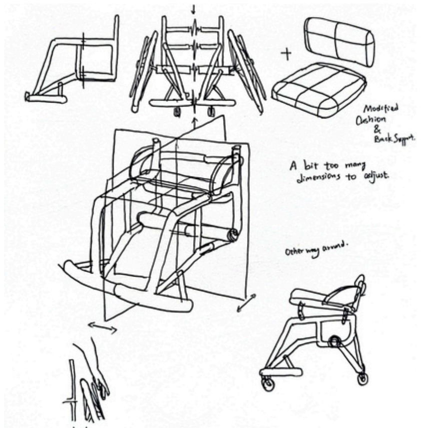
3D printing based solution



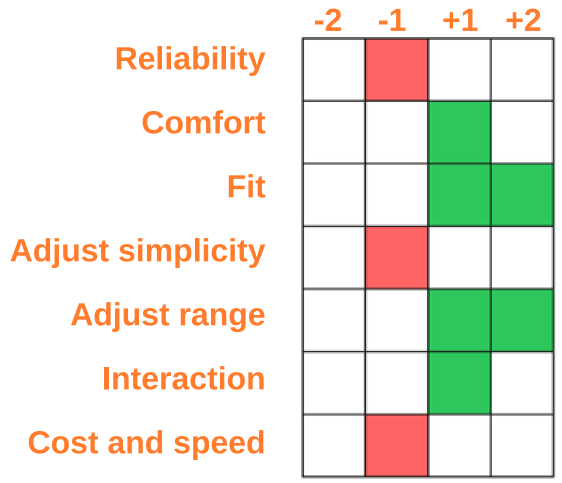


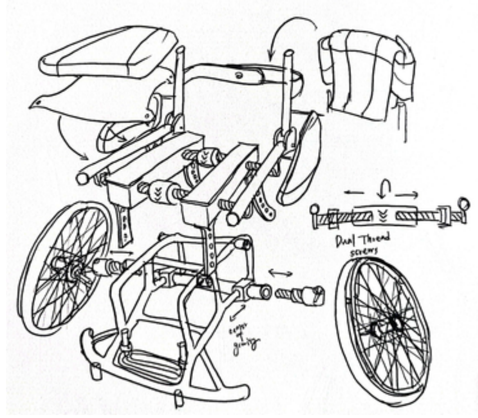
Particle jamming based solution





Frame into pieces solution





Adjustable seat frame solution

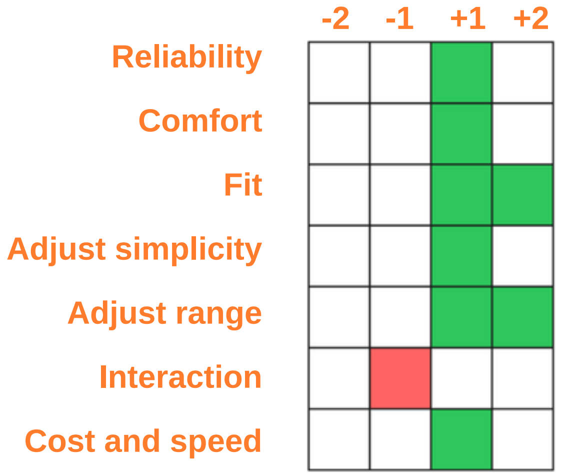
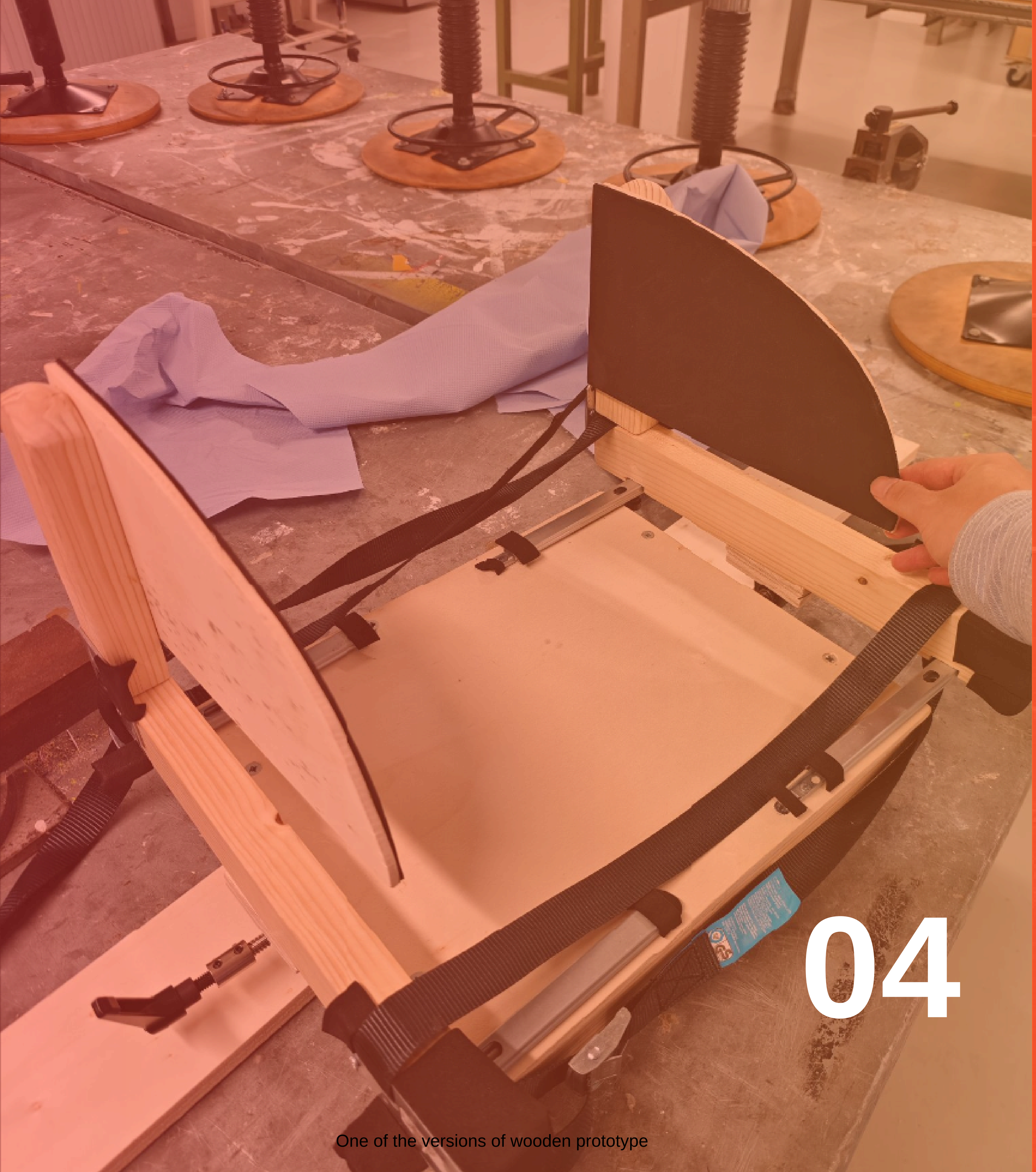


Figure 3.16 Assessment of the concepts using Harris Profile



One of the versions of wooden prototype

04 Realization

4.1 Sizing system

How much should the seat width extend?

Range in existing products

As is shown in Figure 4.1, in general the width adjustment range of existing products is generally between 25-50 cm. While TUDelft *Dined* anthropometric database shows that the hip breath width of an adult is generally more than 30 cm. Since minors and disabled groups who are not fully covered in the database may have smaller hip sizes, a seat width of 25-30 cm still needs to be taken into consideration, especially for minors.

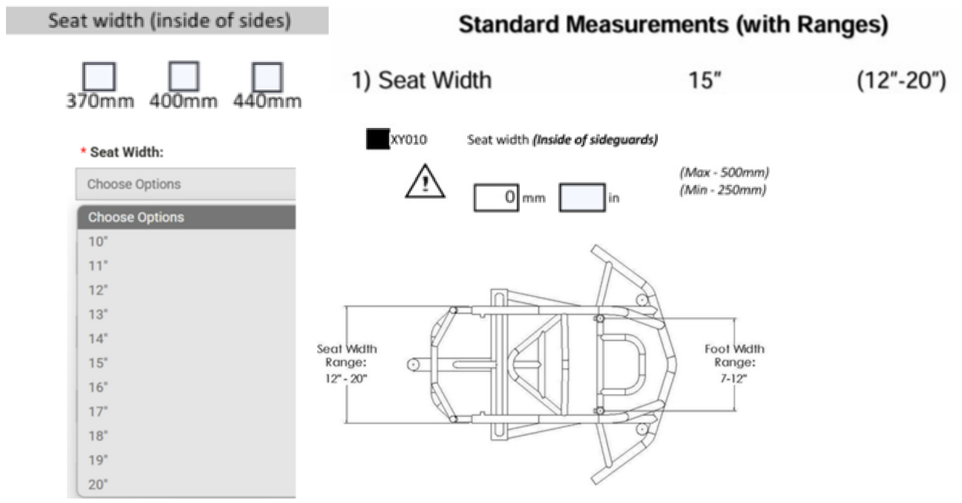


Figure 4.1 Range of seat width found in customization book of existing wheelchairs

Choices of cushion fitting

For seats of varying widths, how the seat cushion adapts is a key issue, and it also greatly affects the choice of the seat width adjustment range. A customized cushion for each user is the ideal solution, but that does not meet the requirements of quick and easy adjustment.

(a)

(b)

(c)

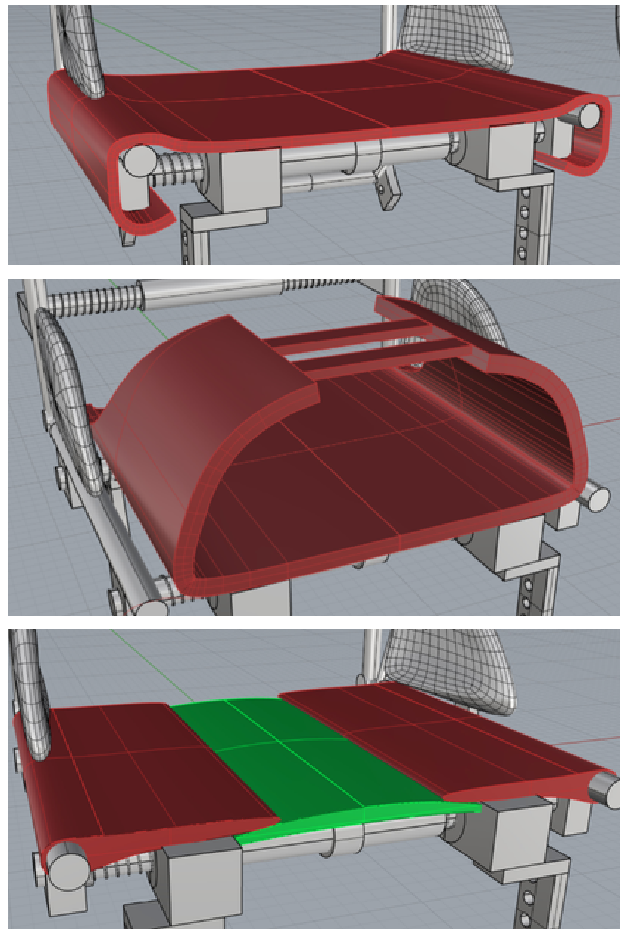


Figure 4.2 Roll down solution (a); Roll up solution (b); Overlapping plates solution (c)

To cover the full range of seat widths, the cushion must reach the maximum width, creating a challenge of managing excessive cushion at the minimum width. Three design alternatives were considered: the roll-down solution hides excess under the seat but disrupts sideguard support; the roll-up solution compresses extra cushion to the side, though its comfort impact is uncertain; and the overlapping-plate solution uses three interlocking pieces that expand or contract with width, but it limits cushion thickness and softness (all in Figure 4.2).

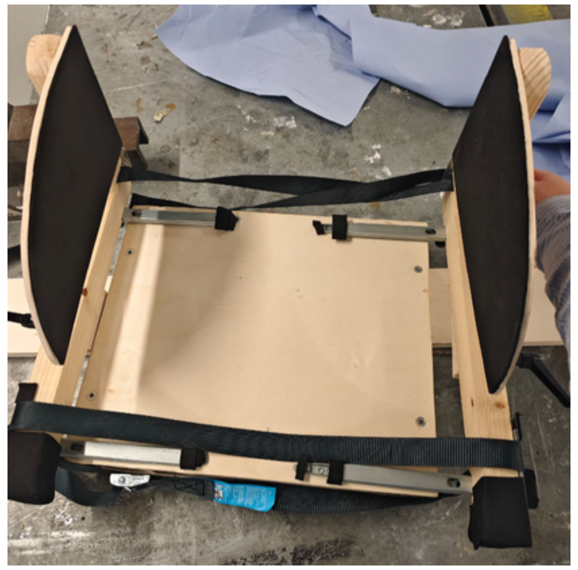


Figure 4.3 Strap based roll down prototype

Based on the roll down solution with a relatively higher level of expected comfort, a design is given in which the seat cushion is fixed to the straps, and the straps are tightened to support the seat cushion and roll it down, as shown in the Figure 4.3. However, straps and clips struggled to support a person's weight, and without an additional tensioning device, manually tightening the straps when adjusting the width was difficult. This design was overly complex and lacked the necessary support for the seat cushion. The necessity of rolling down has been questioned, and optimizing the way of gravity load has become the next direction of optimization.

To optimize load distribution, the fixed seat plane supports most of the user's weight, while the width adjustment mechanism, placed below, bears only a small portion, reducing design complexity.

Structural bars or straps can support seat cushions extending beyond the fixed portion, as shown in Figure 4.4, though friction may require pulleys or rails to improve sliding. In addressing excess cushion width when narrowing the seat, the design squeezes the cushion to the body side with a compensating gap beneath the sideguard (Figure 4.5). This solution minimizes discomfort while raising the sideguard height, enhancing perceived support and overall comfort. It also **helps to maintain a minimum gap between the rear wheel and the sideguard**.

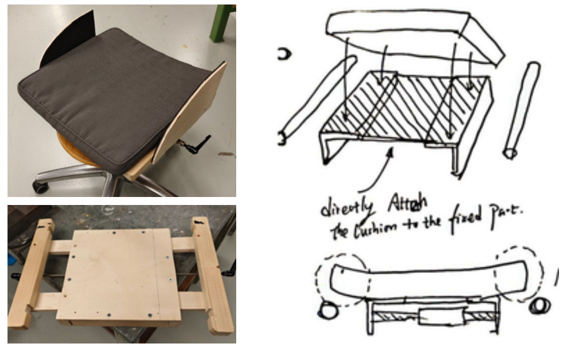


Figure 4.4 Design of seats with structural bars to support cushion

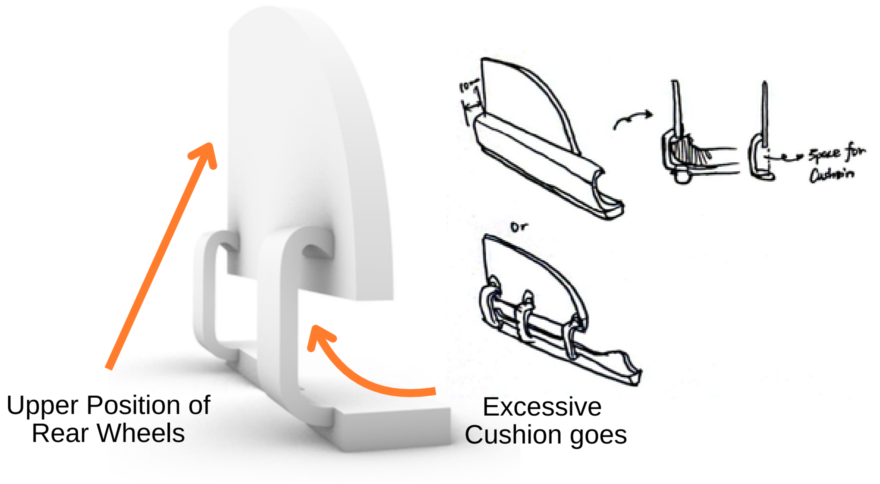


Figure 4.5 Compensating gap below sideguard to contain excessive cushion width

4.2 Width adjustable seat exploration

Modified sizing system

Although hip dimensions do not strongly correlate with other body measurements, product manuals indicate that larger hip sizes generally require a larger lower frame, to which seat width must be adapted. Thus, the 25–50 cm seat width range can be divided into overlapping sizes (small, medium, large). As shown in Figure 4.6, the evenly divided system gives each size a 75 mm range, while the progressive system offers 50–75–100 mm ranges, making it more practical since smaller minimum sizes allow a smaller size of adjustment structures and thus a smaller range of adjustment.

Since the size of the gaps under sideguard at both ends of the cushion won't change, a evenly distributed sizing system is more appropriate for simpler structures, while a more complex adjustment structure may require a progressive sizing system.

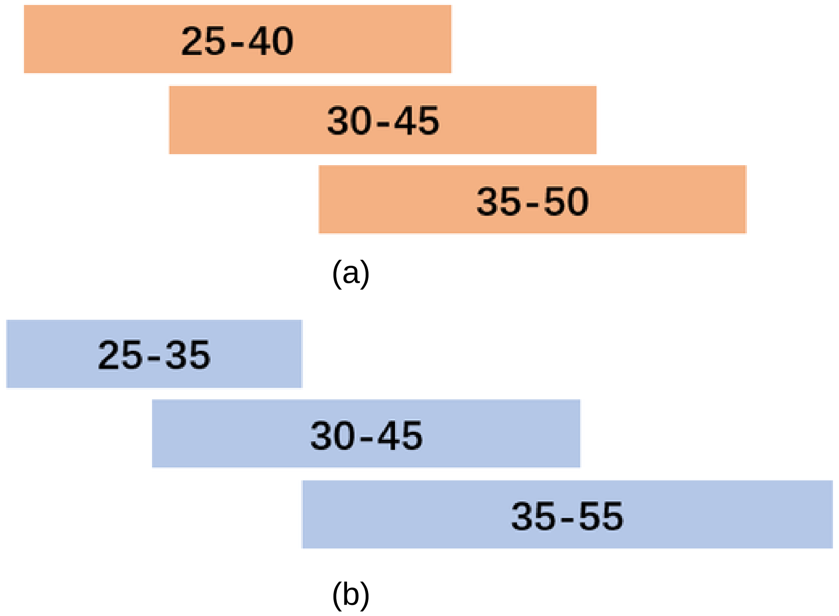


Figure 4.6 Evenly distributed sizing system (a) and progressive sizing system (b)

Initial plan

This part is the key point of the entire design, how to extend the rods on both sides of the seat to achieve stepless width adjustment.

The initial design was based on a given fixed seat connection part, which was used to connect to the lower wheelchair frame, and then two rods extended from this fixed part. The stepless width adjustment was enabled by lead screw rods (Figure 4.7), but how to make multiple rods move simultaneously became a new challenge.

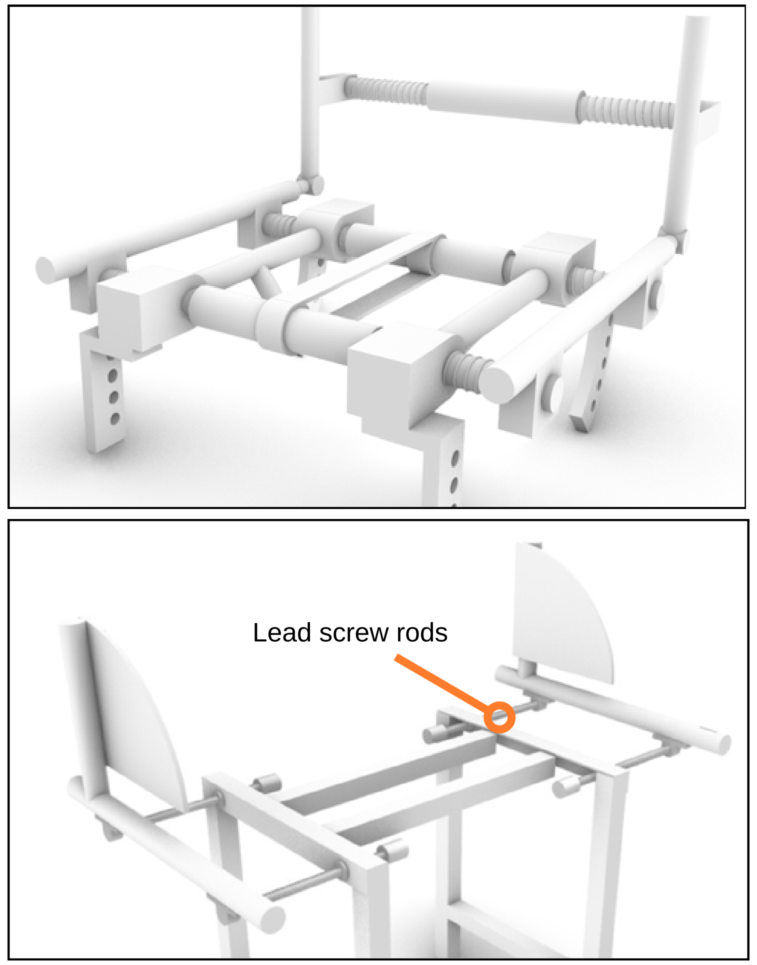


Figure 4.7 Stepless adjustment design enabled by lead screws

Prototype No.1

For prototype No.1 the four lead screw rods (highlighted in Figure 4.8) were simplified to two in the middle position, and four guide rails for drawers were added on both side for auxiliary positioning and support (Figure 4.8).

Takeaways

+The screw rods extending on both sides can be easily accessed and adjusted, providing an additional operating position for the users.

-Blockage happened during the adjustment because two sides of the guide rail was not synchronized, also the guide rails were not completely installed on a flat surface.

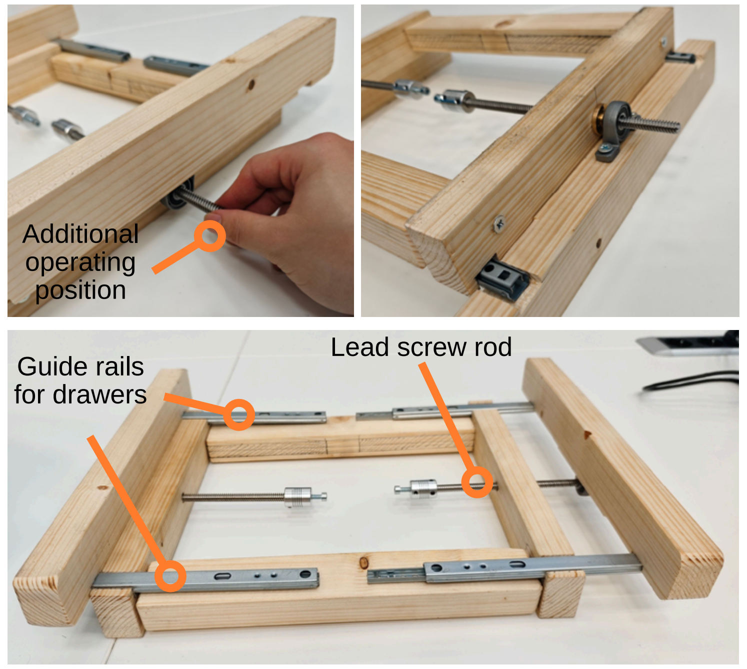


Figure 4.8 Prototype No.1 of simplified lead screw stepless adjustment structure positioned and reinforced by guide rails.

Prototype No.2

To ensure the horizontal positioning of the guide rails, prototype No.2 installed all the guide rails on a flat wooden board. At both ends of the screw rod, handles are connected through couplings to operate the width adjustment (Figure 4.9).

Takeaways

+Installing on a wooden board improve the situation.

-Blockage reduce but still exist, the guide rails were still facing some non-parallel situations. The friction at the connecting position may also contributed.
-The different rotation directions of the handles on both sides also made it difficult to use.
-Cushion on straps didn't work, not stable or operatable.

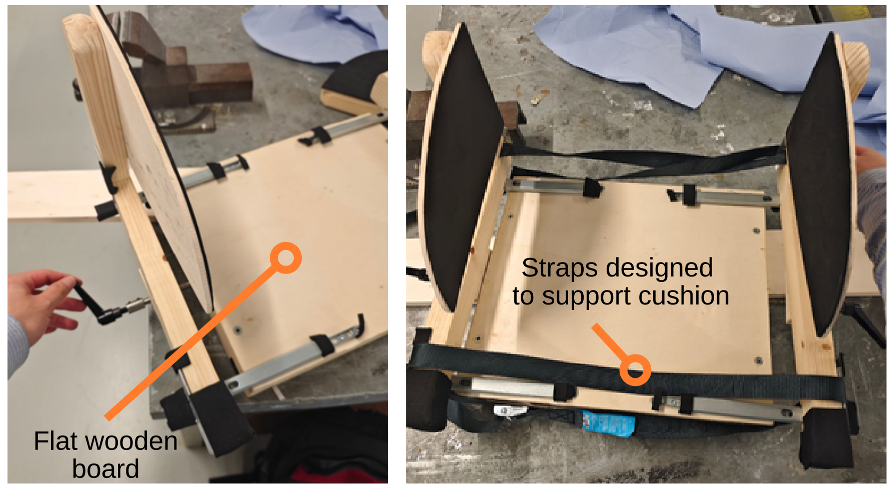


Figure 4.9 Prototype No.2 with all guide rails on same platform

4.2 Width adjustable seat exploration

Prototype No.2 & 2.5

Later, the guide rails were replaced with wooden boards that slid out of the slots (Figure 4.10), which improved stability to a certain extent.

Takeaways

+Sliding boards improved stability.

-Blockage reduce but still exist, the friction and the installation accuracy seems to be the major problems.

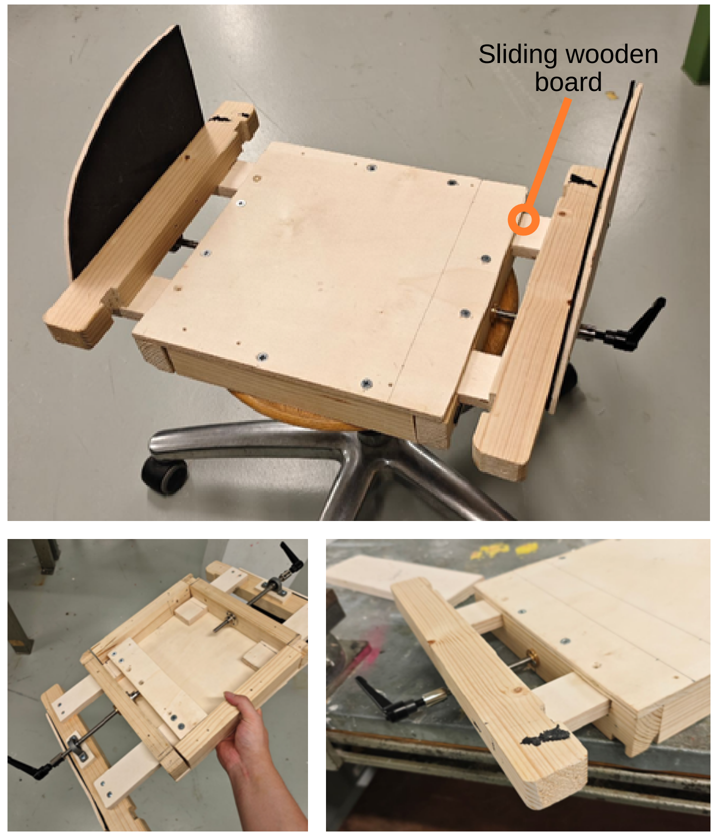


Figure 4.10 Prototype No.2.5 with wooden boards and slots

Turn to 4-bar mechanism

After analyzing prototype No.2.5, optimization should consider avoiding slots or guide rails, and avoid using screw rods to directly connect the extending rods on both sides, in the meanwhile reduce friction contact surface.

The four-bar mechanism driven by the lead screw becomes the first choice, and leading to the development of a variant 4-bar mechanism design (Figure 4.11).

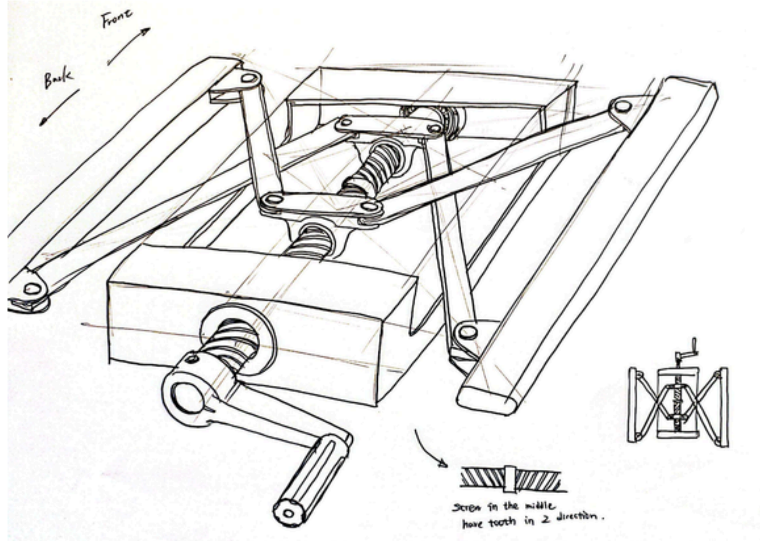


Figure 4.11 Sketches of a variant 4-bar mechanism design

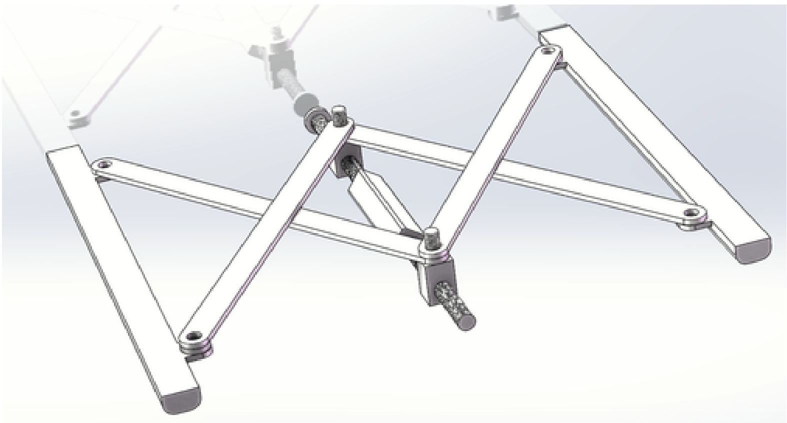


Figure 4.12 Solidworks simulation of 4-bar mechanism design

Scott-Russell mechanism

However, the Solidworks modeling simulations (Figure 4.12) showed that the variant 4-bar mechanism had stability issues, and a slight disturbance could cause the extended rods to be non-parallel. In order to improve stability, the structure is combined with the Scott-Russell mechanism for reinforcement (Figure 4.13). The final result is actually equivalent to the superposition of two 4-bar mechanisms. And the improved mechanism works steadily in Solidwork motion simulation (Figure 4.14).

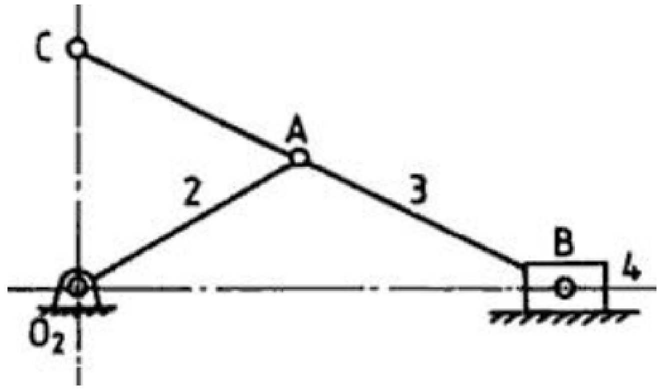


Figure 4.13 Scott-Russell mechanism

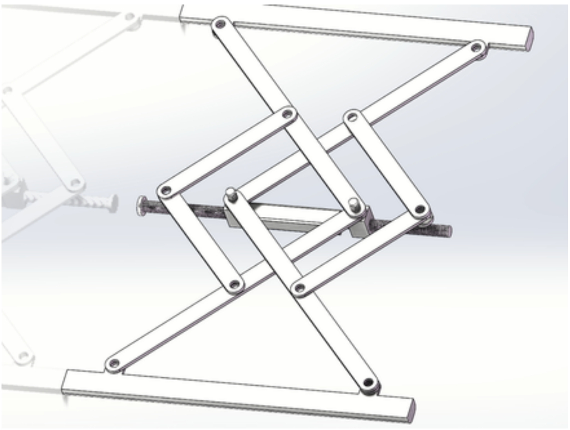


Figure 4.14 Solidworks simulation of 4-bar mechanism strengthen by integration of Scott-Russell mechanism

Prototype No.3

By combining 3D printing, laser cutting, and sheet metal bending technology, the improved mechanical structure was finally realized as prototype No. 3 (Figure 4.15). Additional wooden strips are added under the central fixed part to reduce the tendency of the connecting rod to deform downward.

Takeaways

+New design almost eliminated the blockage issue.

-Misalignment of the limit of the screw rod can easily cause the coupling to disengage, so a more accurate limit method should be considered.

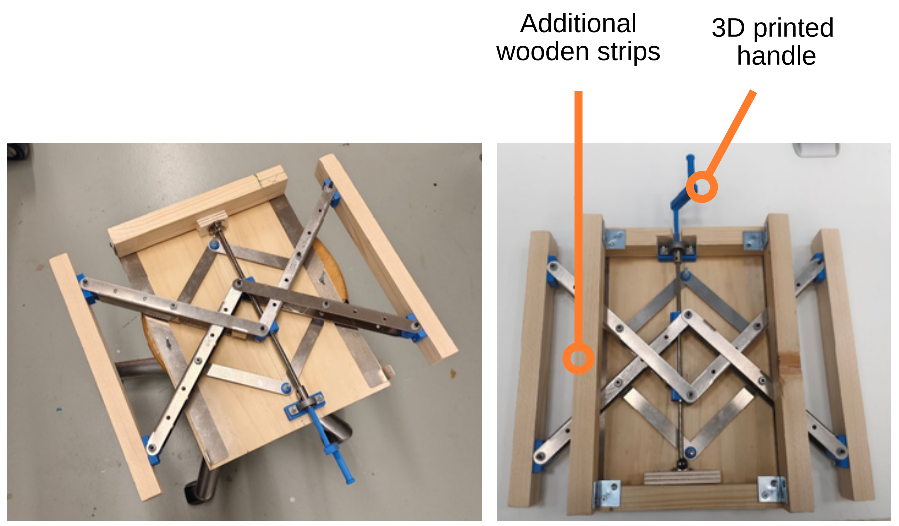


Figure 4.15 Prototype No.3 with improved 4-bar mechanism

4.3 Final prototype

The final seat prototype incorporated the improved 4-bar mechanism from Prototype No. 3, constructed with screws, PETG-printed connectors, and bent aluminum sheet metal, while the extension bars, sideguards, and central section were all made of bent steel sheet metal to improve stiffness and strength (see Figure 4.16). The screw rod limit parts are fixed by laser cutting holes to ensure alignment. Also the wooden bars supporting the connecting rods below are also changed into bent steel sheet metal. In addition, the handle has been changed to a combination of bolts and PETG-printed parts, which greatly improves the feel and rigidity.

By accorporating 4-bar mechanism and using different washers to reduce friction, the seat width adjustment operates much smoother than on any previous prototype.

However, in order to fully validate the design and make user testing as realistic as possible, the seat prototype also needs to be mounted on the wheelchair frame. Since ordinary wheelchair frames differ greatly from basketball wheelchairs and the latter are difficult to obtain, a simulated frame was welded from steel tubes and plates (Figure 4.17).

The connection design was mainly taken from Top End Pro wheelchair, but the central section defines the min seat width while the frame must accommodate larger widths, the seat is connected to the frame with bolts and nylon spacers to maintain sufficient strength.

The use of steel structures for key structural parts makes the entire prototype very heavy, but this choice also ensures its stability and safety during transportation and testing. Also, the white handrails were also installed for easy transportation. To let users feel the backrest during testing, a rod was added to the extension's rear end and connected with a strap. A large number of sponge pads and connectors are installed to avoid possible injuries during the test (the Final version see Figure 4.18).

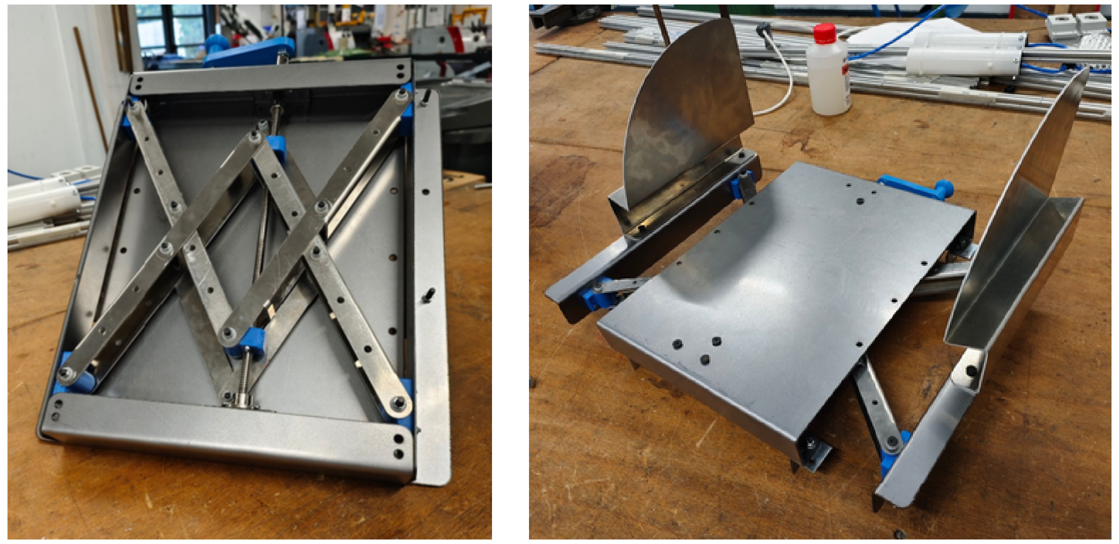


Figure 4.16 Steel shell covered final seat prototype

Figure 4.17 Welded wheelchair frame

Figure 4.18 Assembled final prototype (Top left the final version)

User enjoying the test

05 Evaluation

5.1 Actual user test

5.2 Results and discussion

5.1 Actual user test

To evaluate the design and identify directions for future improvement, a pilot user test was first conducted with friends and the coach, followed by a formal test involving 4 actual wheelchair basketball players.

Test set up

Test subjects:
BS Leiden Rollers team and other wheelchair basketball players could be reached.
Goal:
Figure out how users perceive about the product and function, also what could be improved.
To be prepared:
1) The prototype (Figure 5.1); 2) Tape ruler; 3) Hexagon wrenches; 4) Printed consent form; 5) Printed survey; 6) Camera

Procedure:
1) Get in touch with the coach via email and use his help to arrange for players who are willing and have sufficient English to participate.
2) Users will be introduced to the project and the purpose of the research. Asked to read and sign the consent form agreeing that their anonymized data can be used for research purposes of this project.
3) Users will be asked to **transfer to the product**, and **try to adjust the seat width to reach their perceived perfect fitting position**. **The adjusted seat width will be measured and compared to the their current wheelchair seat width in use.**
4) The user will then be asked to perform simple movements include rotate against the wall and be pushed slightly to move to all directions (see Figure 5.1) .

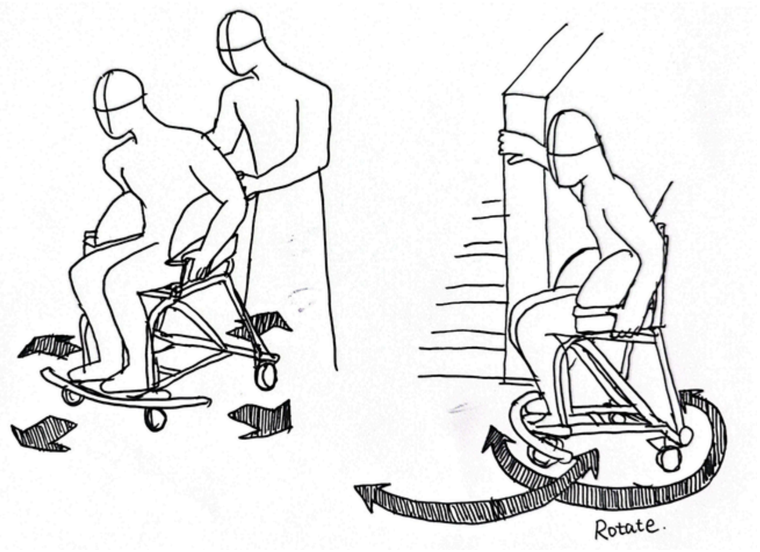


Figure 5.1 Sketches of required movements for users

5）In the end the users will be asked to fill out a survey about the product. Some of the feedbacks will also be discussed in depth orally.

Survey Content:
Which player classification you belong to? (1.0-4.5)___________
1) Borg Scale 0-10
The Borg Scale is a numerical scale (typically 0–10) used to measure perceived exertion or discomfort during physical activity, commonly applied in sports and rehabilitation research. This part of the survey try to use Borg scale to get users' scores about perceived fitting level of stationary stage and moving stage, the efforts it takes to adjust and safety, also how would they like to try different width. Details can be found in Appendix L.

2) Feedbacks
- What features or feelings about the adjustable seat width worked well for you?
- What problems did you notice, or what would you want changed?
- How does this seat width feel in comfort compared to your current chair?

(check the difference of the adjusted seat width and their current seat width)
- In your opinion, what benefits could adjustable seat width bring? (personal / community)
- Other feedback?

Pilot test

To optimize the testing process and better control its duration, pilot tests were conducted with friends and the BS Leiden coach.

During the test process, we realized that some questions might not get the expected results, so the way of asking questions was made more specific to provide more accurate guidance. For example, by adding qualifying phrases such as in comfort, in the process, or in specific features or feelings, the expressions can be made slightly more precise but still left the questions quite open.

At the same time, a side information provided by the coach is that although the basketball wheelchair does not have a lock on the wheels, it is usually placed against the wall to ensure transfer stability. This requires special attention in the subsequent testing process.


Figure 5.2 Final prototype for testing placed in IDE

Since the participants in the pilot test were all healthy people, they were able to directly drive the wheelchair through the strength of their lower limbs, but this is impossible for wheelchair users, so appropriate movement methods must be designed to allow them to feel the fitting level in the moving stage. Taking into account the existing conditions, **a combination of passive propulsion forward, backward, left and right movement, and autonomous movement and rotation against the wall** was selected to simulate the movement scenes of wheelchair basketball under the low load conditions. It also ensures that less testing space is occupied and the training session of players is not interfered with.

5.2 Results and discussion

User test

As planned, user testing took place at the Sportzaal Houtkwartier Leiden with the BS Leiden wheelchair basketball team(test environment see Figure 5.3). The activity was welcomed there, and their coaches actively tried it and offered sufficient support. However, due to an unexpected language barrier, only one team trained that day and some players did not speak enough English to fully cope with the test. Nevertheless, the experiment was completed with 4 active participants representing different user groups and possessing adequate English comprehension skills.

Figure 5.3 Prototype and the testing scene at Sportzaal Houtkwartier Leiden

Test results

All the answered survey can be found in Appendix P. The classification scores of the four participants were 1.0, 2.5, 3.5 and an unrated newcomer with an estimated score of around 3.0, so they are representative in terms of user composition. And the results of their Borg scale 0-10 is shown in following Figure 5.4, and questions see Figure 5.5.

Although the scale extended beyond physical intensity, **participants' overall feedbacks of the prototype were positive**. Average scores for all items were below 5, with the highest score approaching neutrality, indicating **general satisfaction with the design.**

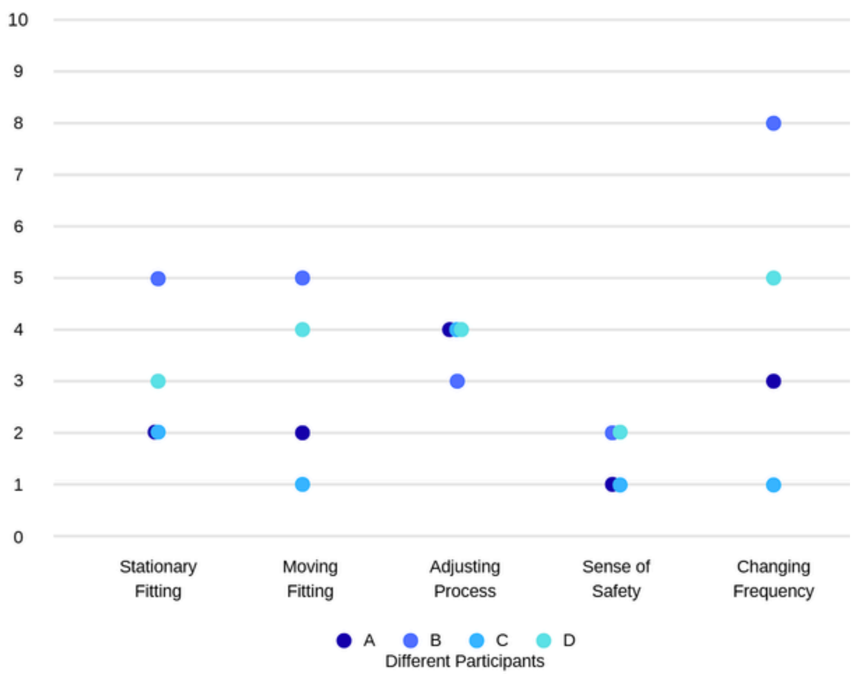


Figure 5.4 The scores of the 4 participants on each question, Vertical axis shows the scores, horizontal axis shows the setting.

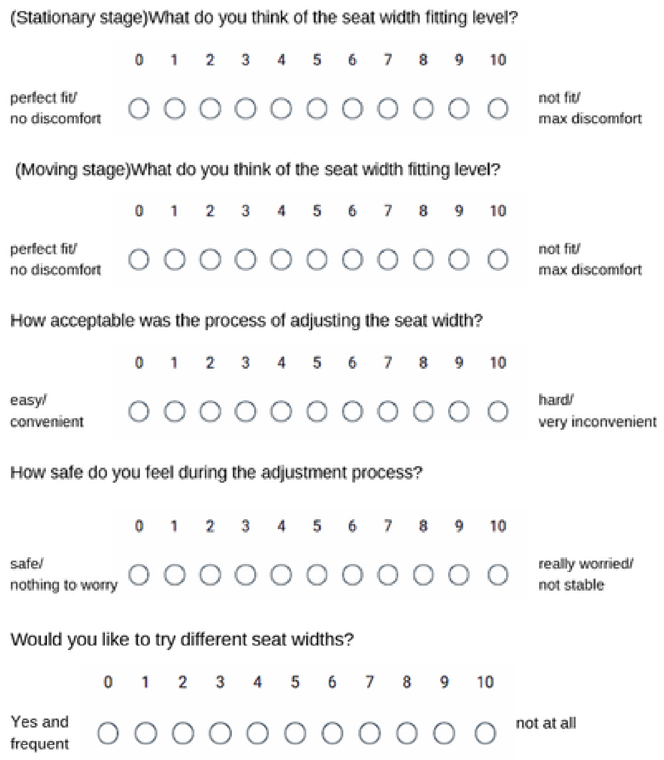


Figure 5.5 Five questions participants given scores on

The results indicate that seat width adjustment is satisfactory, with **no significant difference in stationary or moving seat width fit**, all reached the same average of 3. They tried to sense it but the difference was not noticeable (Figure 5.6). However, some fluctuations in the moving stage score are related to **the lack of a strap in the test prototype, which is crucial for stability during movement**. In the later feedback session two participants told me that, one of them excluding this influence and the other taking it into account, ultimately reached a consistent average.

Regarding the adjustment process, they generally had some **concerns about the handle position**, but at the same time emphasized that the current state was acceptable, and therefore generally gave it a score between 3 and 4. However, they had no doubts about safety and stability, with the average score being as low as 1.5.

Responses to the last question varied, with newcomers considering seat width adjustment unnecessary once an appropriate fit was found, while experienced players generally **recognized the value of varying widths in daily life for example when physical condition changes**, though with differing frequencies.

Figure 5.6 Participants tried to better sense the seat width as they completed the survey

5.2 Results and discussion

Results & Feedbacks

The feedback session was even more exciting, with participants providing unexpected feedback and adding more value to the width adjustment feature.

Initially, the design's original intent was well-recognized. Most of them noted its value **for developing players**, emphasizing that the current minimum five-year replacement cycle doesn't meet user needs. Meanwhile, newcomer B, who happens to be using C's previous wheelchair, found it too wide for him, and appreciated the width adjustment feature for **sharing context**.

Participants also recognized some added value of adjustability. The handle design was appreciated for enabling **one hand operation** on both sides, which is relevant since some players have limited movement in one hand, and quite interestingly three of the four participants were left-handed, indicates that operation position needs to consider both the left and right sides equally. They highlighted the **benefit of adjusting the wheelchair each time they sit in it**, noting that **seat width may slightly vary** with factors such as food intake or weight change. Two participants further indicated that **post-seating adjustment makes transfers easier and allows for a closer fit** because they don't have to squeeze their body during the transfer. The data shown in Figure 5.7 also confirms this: the seat widths of B and C after adjustment are smaller than their current seat widths.

In terms of negative aspects, their opinions were largely consistent. They all noticed that the handle can be improved. Although the expressions were different, some thought it was not smooth enough, some thought it needed an adjustable backrest, and some thought the position should be adjusted, but the essence was that the prototype did not have a complete backrest and the handle was too close to the back, which made it easy for participants to sit too far back and the **buttocks interfered with the handle** (Figure 5.8). And it happened with all the participants, which can be found in Appendix P. Also, participants with lower classification scores concerned that players with higher paralysis might not be able to reach the handle because of their limited movement.

In the process of expressing themselves, they showed a preference for independence, and they also mentioned that this problem was not particularly serious. They all used "**fine**" to evaluate it, like, "**the handle position can be changed, but now is fine, because you can reach it and that's enough...**"

The difference between their adjusted seat width and the current seat width was also discussed. As shown in Figure 5.6, their adjusted seat width is the same as the current one or even tighter. Adjusting the seat width to the perfect fit provides a fit that is **equal to or even better than the current one**. And participant D's result is special because his existing wheelchair does not have sideguards, and the seat width when used without restrictions on both sides is larger than the actual measurement, thus makes the seat width after adjustment wider than the his current one.

During the measurement and comparison process, it was found that most **sideguards have an unified inward curvature**, which better fits their general body curve, rather than the flat state of the prototype. At the same time, one participant also pointed out that her wheelchair has **a significant inward tilted sideguard to fit her leg** (shown in Figure 5.9), which is a regular setting for slim players, and she added that players with lower scores may have noticeable **left-right asymmetry**.

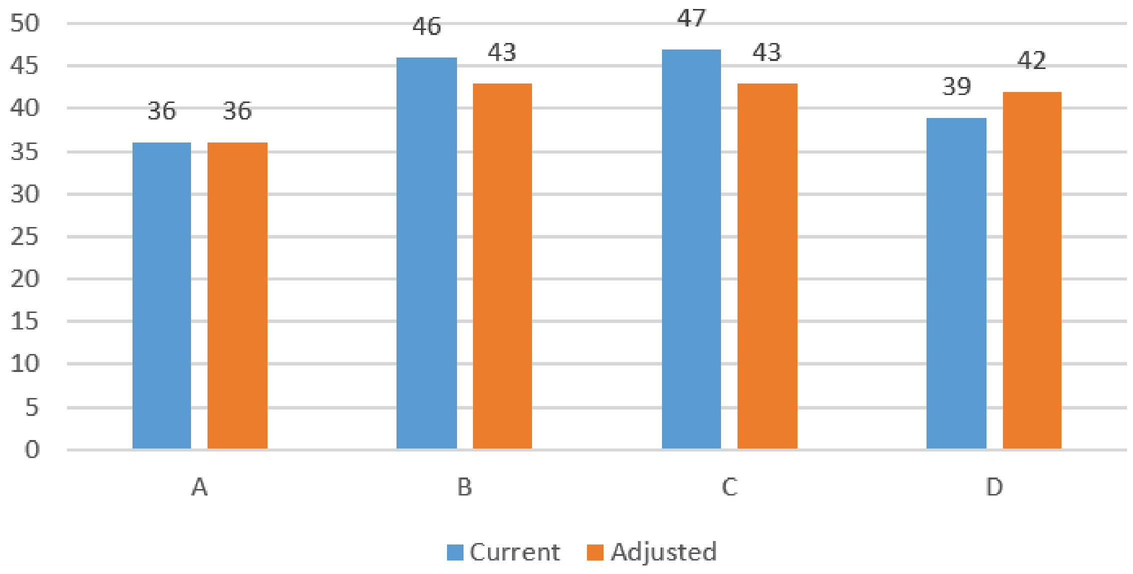


Figure 5.7 Comparison of current and adjusted seat width, vertical axis shows the width in cm, horizontal axis shows the code of participants

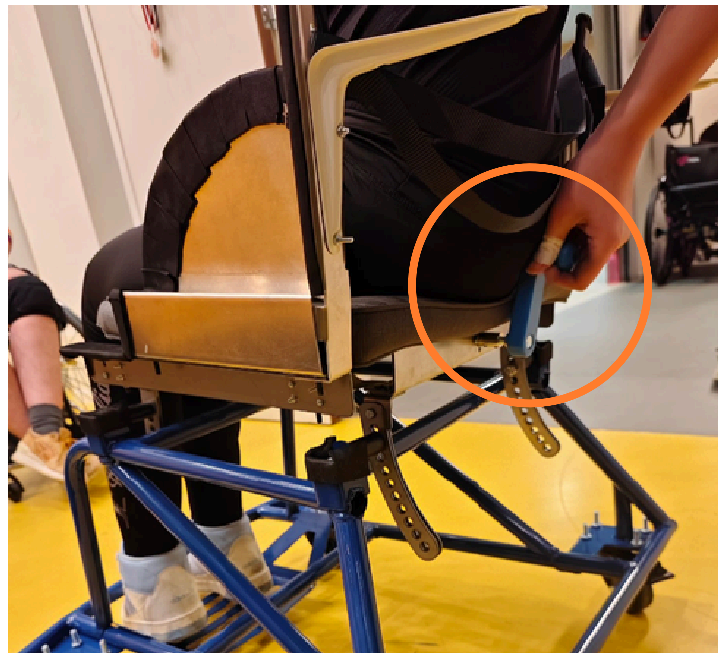


Figure 5.8 Body interfered with handle

Figure 5.9 Inward tilting sideguard wheelchair

5.2 Results and discussion

Limitations

Fortunately, the coach and players at BS Leiden rollers cooperate really actively and the test was carried out in a quite enjoyable way. It's still pity that many players did not participate due to insufficient English proficiency. Although participants after the third provided no significant insights, four participants were sufficient, but if language barriers had been carefully considered, having eight or even ten participants could expect some interesting data outcome.

In terms of survey design, the use of the Borg scale throughout the survey caused confusion among participants, as they were more accustomed to higher scores for more positive responses. However, these issues were modified after sufficient prompting.

Figure 5.10 Comparison of the prototype and the wheelchair it simulates

Most notably, due in part to unclear expectations regarding feedback and limited testing experience, the questions remained relatively open despite the inclusion of some guiding terms, resulting in feedback that was not always directly related to specific design decisions.

On the one hand, it is inevitable that one person will be in a hurry when hosting such a complicated test, resulting in certain procedures and instructions not being fully implemented. For example, tightening the backrest straps and introducing the handles in advance were seriously neglected. These measures are also helpful in obtaining feedback on specific design decisions.

On the other hand, the prototype failed to perfectly simulate the configuration of a real wheelchair (comparison in Figure 5.10). Due to time and scope constraints, the backrest and rear wheels, which should coordinated to seat width adjustment, were not fully designed and implemented into the prototype. This made it difficult for participants to fully replicate real world wheelchair basketball movements and also caused interference between the handle and the buttocks. Also, the cushion should be fixed to the seat to avoid squzeeing it out.

However, it is worth mentioning that despite the many restrictions, the participants were still very enthusiastic (Figure 5.11). They all showed a high willingness to cooperate and hoped to receive more updates in the future.

Points for design improvement

Optimize Handle Position

Problem: Buttocks interfered with the handle during the adjustment, and paralyzed players may not be able to reach the handle. Also it should be remain equal for left and right hand as well as independent,

Action: The distance between the handle and the rear end of the seat will be extended to avoid interference, and the position of the handle is slightly raised through gear transmission to make it easier to reach.

Strap system

Problem: Prototype without straps around the thigh and knee was unstable during movement. Also someone complaint that his current strap position is not comfortable.

Action: Adding multiple holes on the front side of the extension bars to install straps at different position.

Sideguard Surface

Problem: The prototype's sideguard is completely flat, while their wheelchair's sideguard has a certain curvature.

Action: Adding curvature and a bit of elastic surface to the sideguard as previously designed

Sideguard tilt

Problem: Someone has a pair of inward tilting sideguards to fit slim legs or legs with muscle atrophy.

Action: Adding spacer to adjust the front and rear position of the middle screw rod, and then a tilting angle is added to the extension rod by changing the position of the screw rod.

Asymmetry

Problem: Players with lower classification score may have asymmetry on left and right side of their hip.

Action: Adding spacers that can be swapped left and right at the connection point between the seat and the frame, so that the left and right position of the seat relative to the frame can be adjusted.

Backrest & Rear wheel

Problem: Missing backrest and rear wheel adjustment in the prototype.

Action: A preliminary solution is provided for the final design, but further extensions are left to future work.

Figure 5.11 Users enjoying the test

Rendering of the final design

06 Final Design

Product in use

The Final Design solution adopted most of the settled design from the final prototype, but also included adjustments based on the user test, such as changed handle bar position, added strap system and solution to sideguard tilting and asymmetry.

Basic adjustment function

Since the design was based on existing wheelchair Top End Pro basketball wheelchair, most of the currently existing adjustable dimensions are adjusted in the same way as the Top End Pro wheelchair (Figure 6.1 shows the comparison).

The seat height and angle adjustment will be enabled by the strips with holes at the four corners of the center frame of the seat. The backrest angle using similar multi-hole plates with holes corresponding to backrest angle different angles. While seat depth and backrest height adjustment still require additional configuration pieces on the front end. At the same time, the center of gravity adjustment adopts the method used by RGK Club Sport to adjust the anti-tipping wheel and rear wheel axle assembly on a parallel rod (Figure 6.2). Not all of them can be adjusted while sitting, but none of them are very difficult to adjust and can be completed in less than fifteen minutes.

Figure 6.1 Comparison of Top End Pro and the final design solution

Figure 6.2 Centre of gravity adjustment

Seat width adjustment

The seat frame is similar to the original separate seat design of Top End Pro wheelchair, connected to the lower frame through four connecting strips with holes. And the seat width adjustment mechanism is installed inside the frame (see Figure 6.3) as an additional layer under the cushion support. The four-bar structure is fixed to the seat frame and connects the side rods.

Before making critical seat width adjustments, quickly remove the rear wheel to avoid interference. Then relax the restrictions of the backrest and install a handle with an inner hexagon and a limit slot at the rear end of the seat (Figure 6.2). This step can be done while sitting in the seat or it can be installed before transferring to the wheelchair.

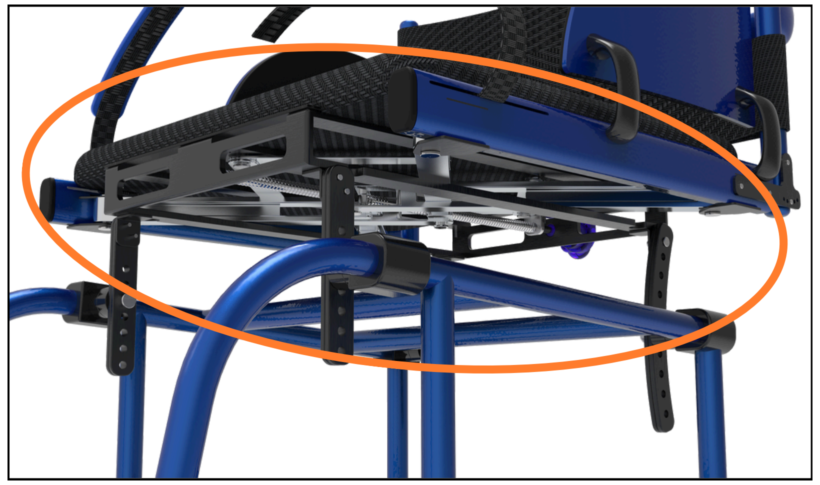


Figure 6.3 Seat frame installed with width adjustment mechanism

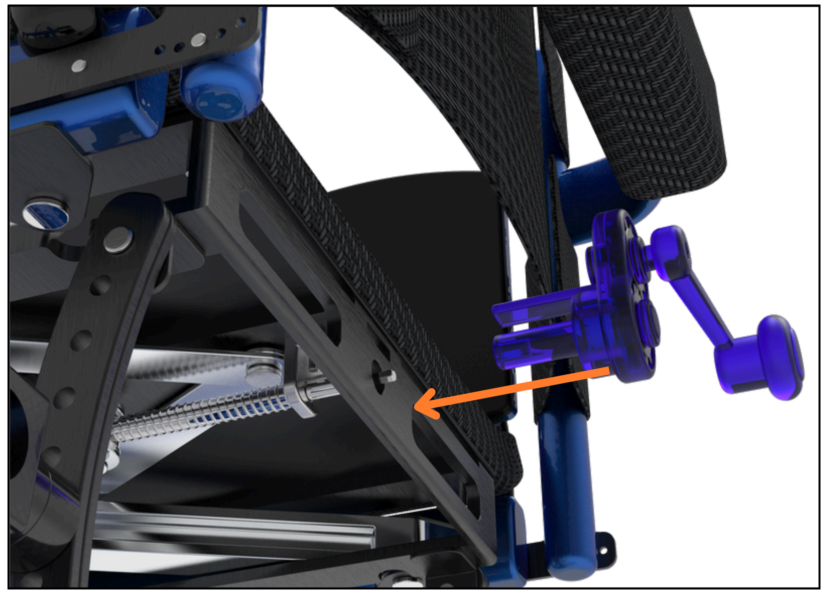


Figure 6.4 Installing the handle at the rear end of the seat

When the handle is well installed, the player can then sit in the wheelchair, reach the handle, and adjust the seat width by turning it. Once the perfect seat width is achieved, the backrest should be fastened and the distance between the rear wheels should be adjusted according to the adjusted seat width. Finally, the rear wheels are installed. The design of these two aspects is only included as design proposal and future direction.

6.2 Product explained

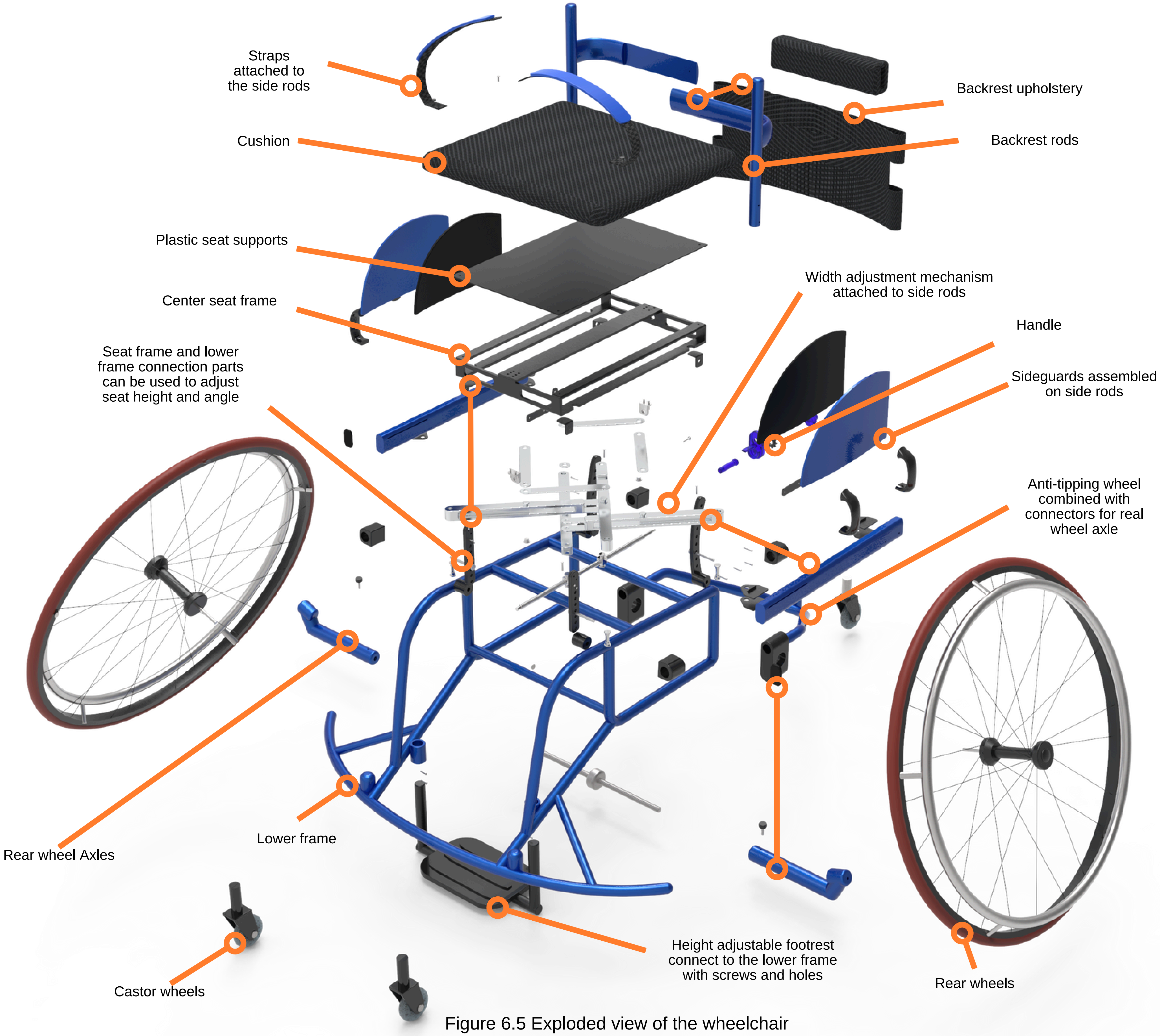


Figure 6.5 Exploded view of the wheelchair

Exploded view of the design

The Final Design solution involves a lot of parts and components (Figure 6.5), but not all of them are fully designed. The design focus is on the structure and frame of the seat width adjustment (Figure 6.6).

Figure 6.6 Views of different layers of the seat adjustable frame

6.2 Product explained

Seat adjustment mechanism

Compared to the final prototype, the final design used solid aluminum alloy parts instead of sheet metal parts to improve strength, and also designed an I-beam structure to reduce weight. The center seat frame was also reduced in weight by removing unnecessary parts and creating slots (see Figure 6.7). In order to ensure sitting comfort, plastic leather consistent with the seat of a general wheelchair is fastened on top of the frame to form a complete support surface. The final design seat width adjustment mechanism operates in the same way as the final prototype (Figure 6.8 & 6.9).

Since the steel plates used in the prototype are relatively heavy, it is necessary to verify the weight issues in the design. The volume of the aluminum alloy (only the portion shown in Figure 6.7) obtained based on the model is approximately 600 cubic centimeters, and the weight calculated based on the density is around 1600 grams. And this does not include the weight of the original seat frame. Based on the previous research, this added weight can be considered acceptable.

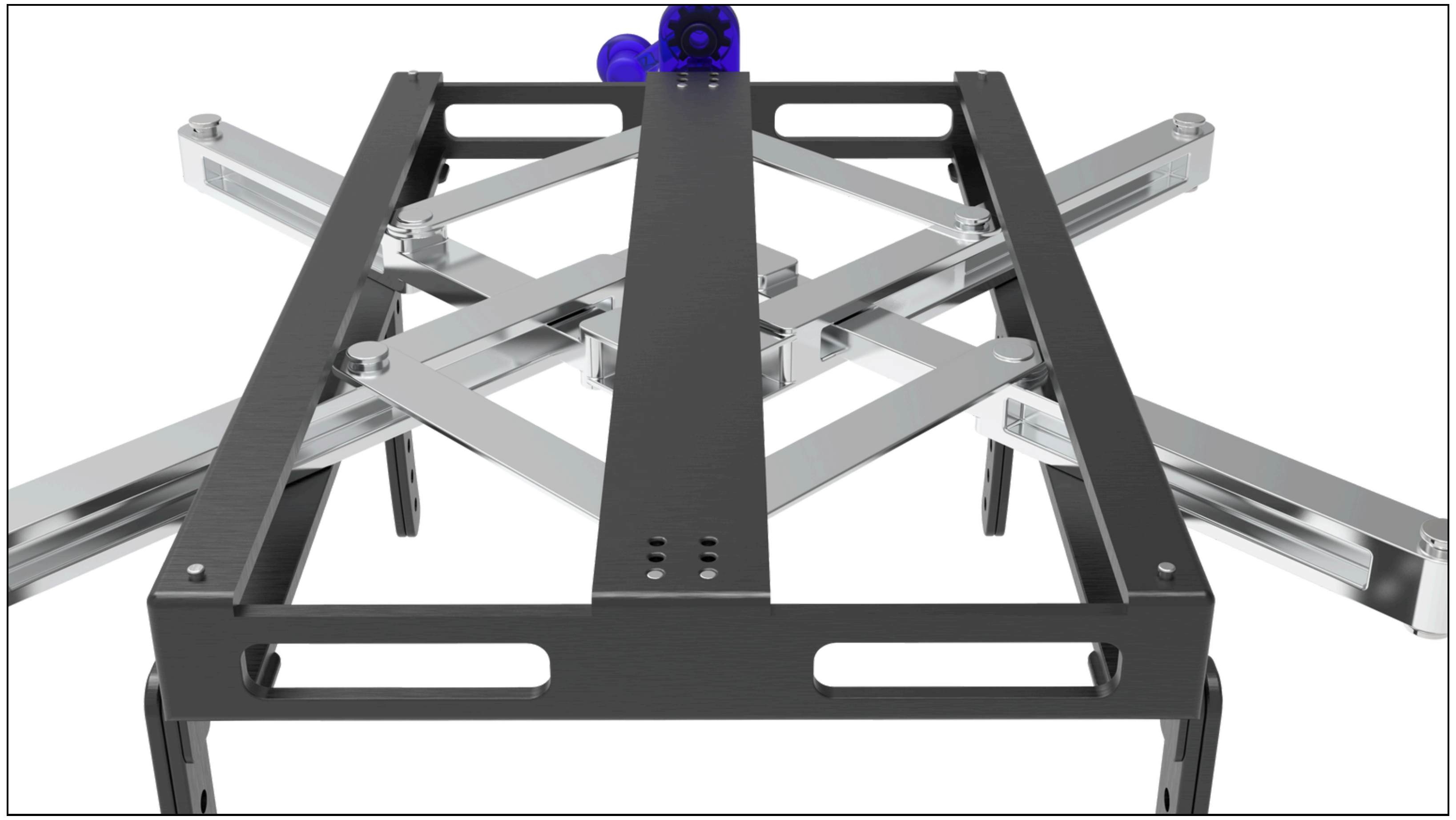


Figure 6.7 Finalized central seat frame and 4-bar mechanism

Figure 6.8 Narrow and Wide seat width adjustment mechanism

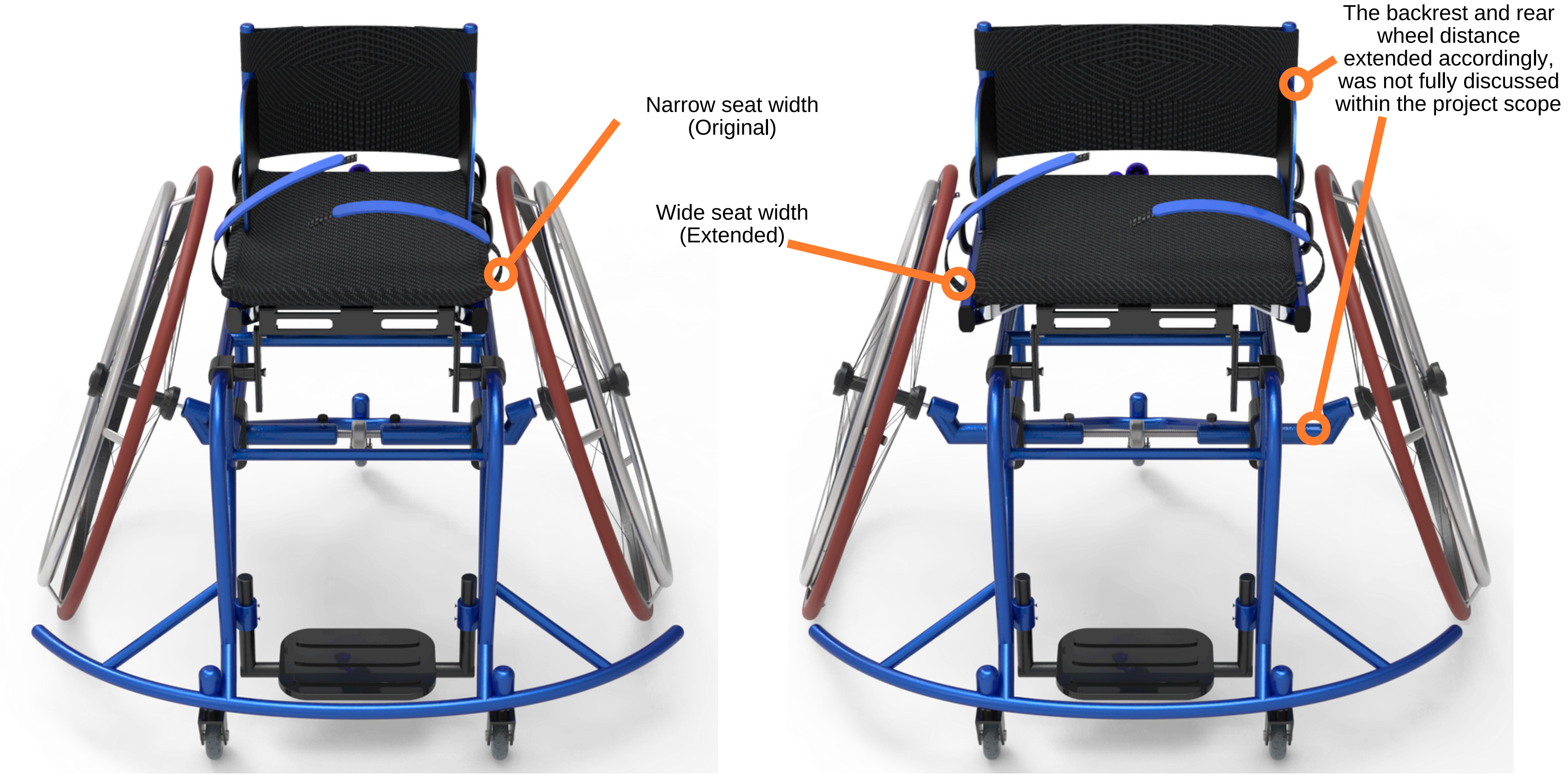


Figure 6.9 Narrow and Wide seat width adjusted

6.3 Design improvement proposals

In response to the findings from user test, the following design details are proposed. There was no sufficient opportunity to conduct prototype verification within the project scope, but some of the structures are relatively simple, while some of the structures and functions can be realized in the existing prototype.

Changed handle position

To avoid interference, the length of the rod connecting the handle and the seat was lengthened. At the same time, to make it easier to reach, the handle's rotation axis was moved up 10cm through two gear transmission (Figure 6.10 shows the position difference, Figure 6.11&6.12 compare the original and redesigned handle bar), hexagon connector and a limit slot ensured that the relative position of the two gears was perpendicular to the horizontal plane.

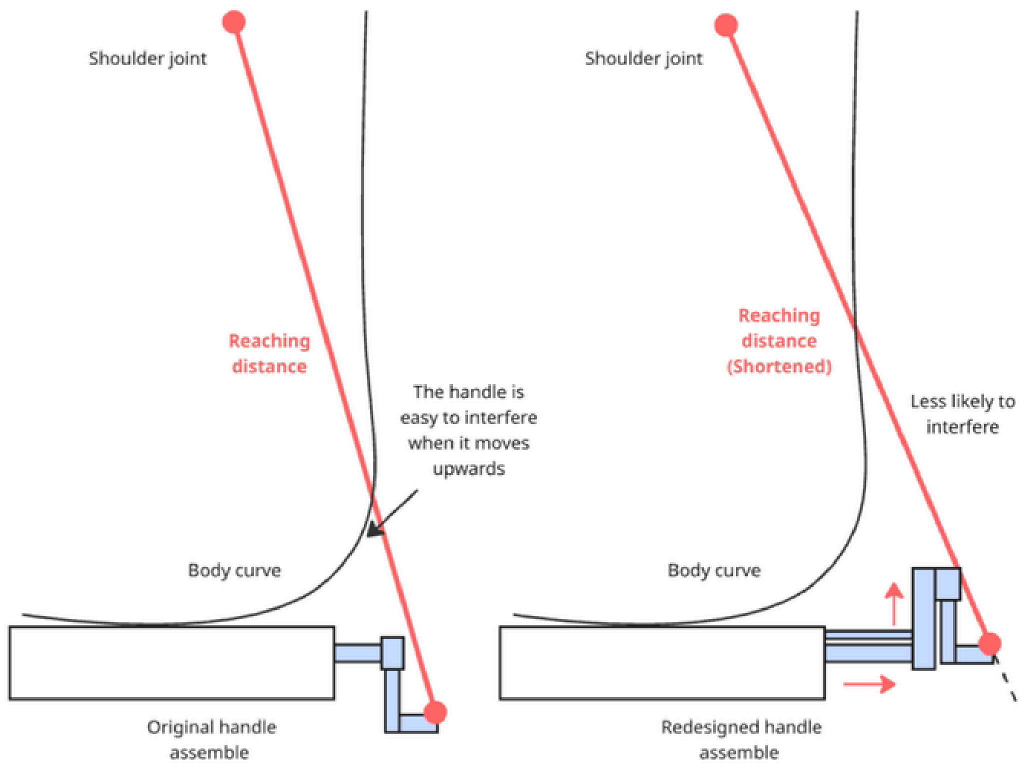


Figure 6.10 Diagram of handle bar position optimization

Figure 6.11 Original handle bar on the prototype

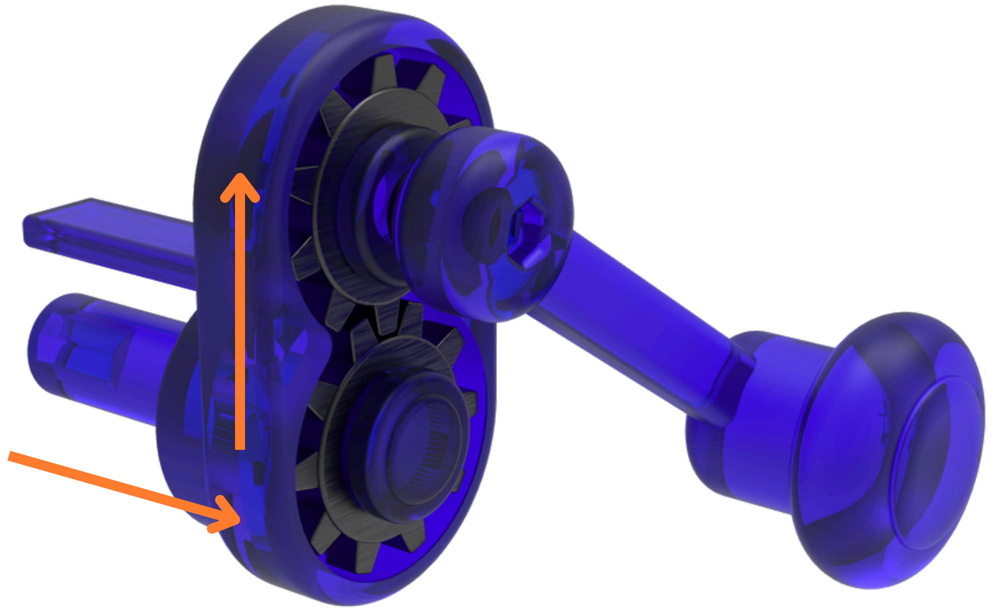


Figure 6.12 Redesigned handle bar

Added Strap system

In order to achieve the adjustable position of the straps, a long slot (Figure 6.13) is suggested to be placed on the extension side rods at both ends of the seat, and the strap can be fastened to different positions of the slot by bolts.

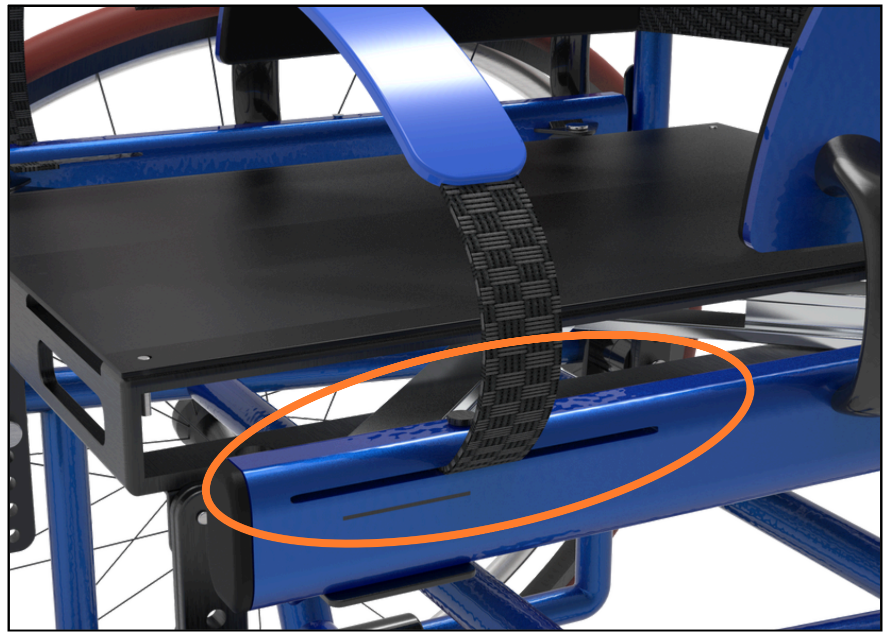


Figure 6.13 Slots on extension bars to adjust the strap position

Sideguard surface

The sideguard is adjusted to have a little bit inward curvature, and a thin rubber protective layer is added to the inside of the aluminum plate to improve comfort (see Figure 6.14). Since the seat width needs to be adjusted a bit bigger in advance, it will not have much impact on getting into the seat.

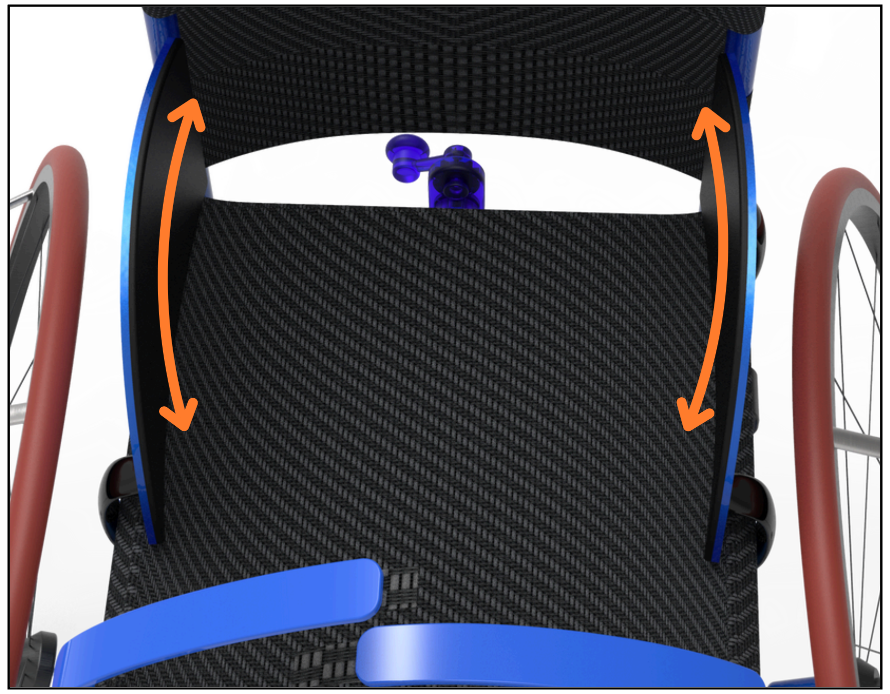


Figure 6.14 Curved sideguards

6.3 Design improvement proposals

The following two solution proposals correspond to physical conditions commonly observed among players in the low-scoring classification; however, the size of the specific population to which they apply remains uncertain.

Asymmetry

Four pairs of nylon spacers (Figure 6.15) assembled at the four corners of connecting points to make up for the gap between central seat frame and the lower frame. When a player's left and right hips are asymmetrical (Figure 6.16&6.17), one of the spacers on one side can be moved to the other side, changing from a pair on each side to one spacer and three spacers, thus achieving asymmetrical adjustment. This can also be seen as adjusting the lateral center of gravity.

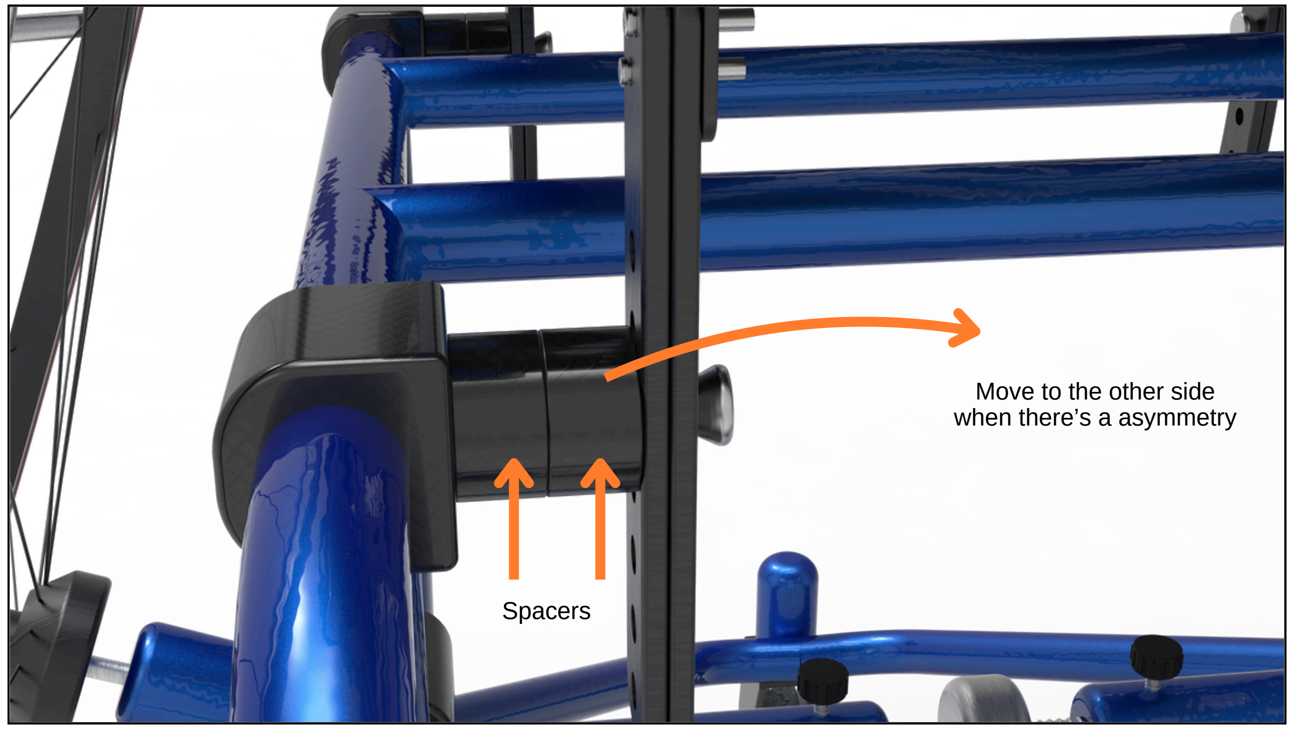


Figure 6.15 Pairs of spacers at the four corners of connecting points

Figure 6.16 Asymmetry caused by differences in the status of the left and right legs

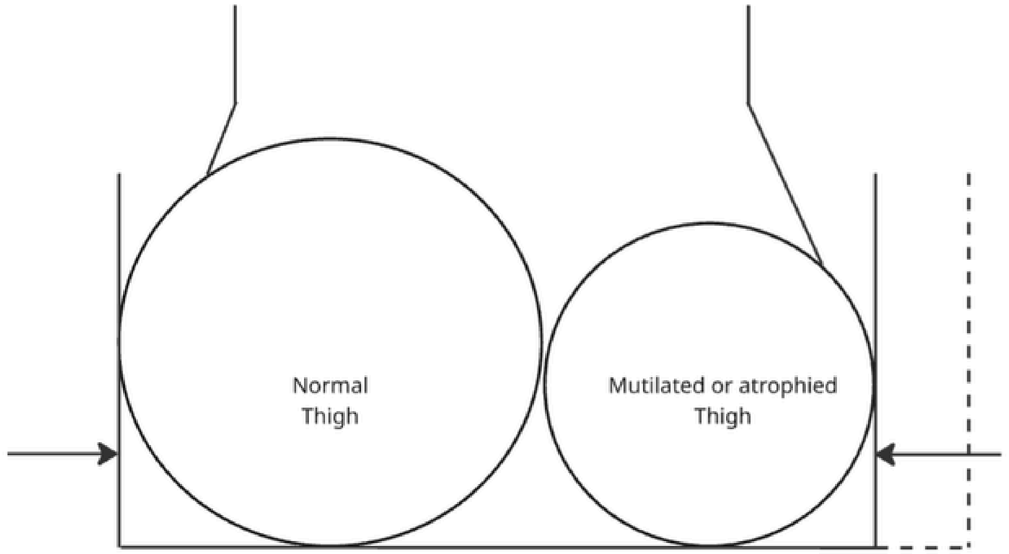


Figure 6.17 Diagram of asymmetry around the hip

Sideguard tilt

This is designed for players who are very slim or have muscle atrophy. Three rows of holes (Figure 6.18) are drilled in the central seat frame at each end to fasten the lead screw limiting parts (Figure 6.19). When the sideguard needs to tilt inward, the two limiting parts simultaneously moved rearward and fastened using the rear row of holes. This positions the lead screw rearward relative to the frame, while the middle link bars attached to the frame remains in place. This allows the extension rods and the sideguard to tilt inward together, a phenomenon also verified in earlier prototypes.

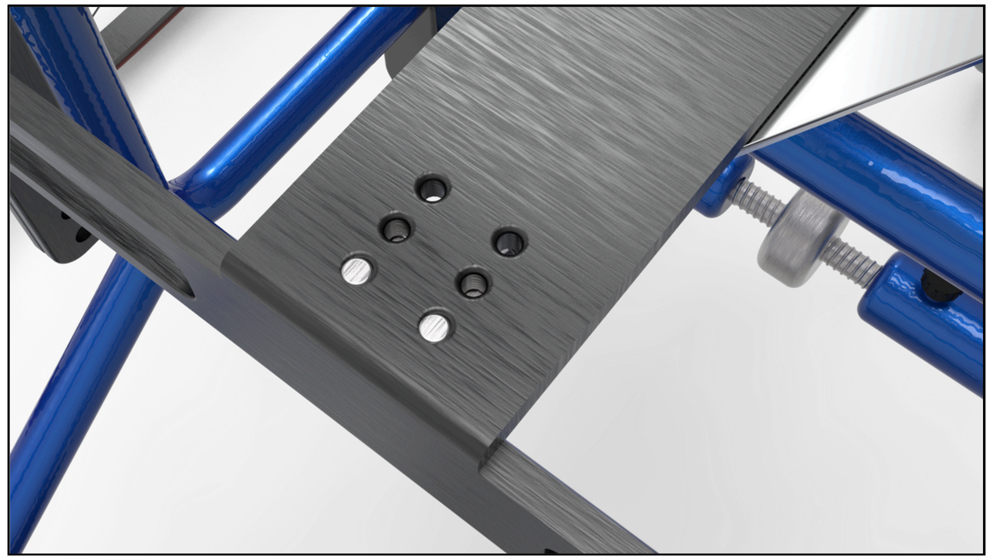


Figure 6.18 Holes on the middle of the central seat frame

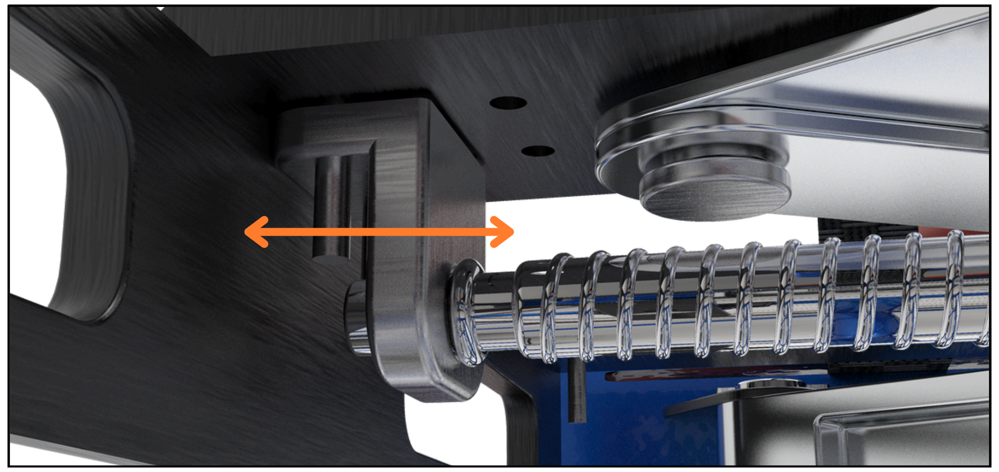


Figure 6.19 Viewed from below: the limiting parts used to fix the position of the lead screw rod

6.4 Future work

Reviewing on the list of requirement

As the final design and proposals are conducted, it would be nice to have a look back on the list of requirement concluded in the earlier chapter 2.4.

Although not every requirement has a specific corresponding implementation, they indicate the essential factors that should be considered during the design process and provide valuable guidance for both the earlier prototyping phase and the final design. Certain aspects have yet to be fully validated and will require further testing and verification in future work.

Category	Requirements	Current stage
Basic features	• The size and range of adjustment of the wheelchair should comply to IWBF rules. Include seat height, anti-tip castors, backrests and legroom.	Applied as a sizing guide for prototypes and designs
	• Wheelchairs must be strong and reliable enough to take the load of high-intensity competition maneuvers; ensure the safety of the user.	Taken into consideration yet not well justified (see 5.2 limitations)
	• The design of the wheelchair should be able to accommodate different configurations, such as wheel size; camber angle; seat dimensions.	Achieved by integrating existing wheelchair structure (see 6.1)
	• Added features and components must not disrupt basic functionality; shorten the lifespan; have negative impact on wheelchair performance such as propulsion efficiency.	Factors like rear wheel distance still need to be designed and tested (will be mentioned in 6.4)

Category	Requirements	Current stage
Adjustability feature	• The adjustability of the wheelchair should accommodate users' rapidly changing fitting needs. Adjust to fit one user's changing need; Adjust to fit different users.	Tested with different users (see 5.2)
	• The adjustability of the wheelchair should integrate existing parameters such as seat height, seat depth, center of gravity and backrest angle, while incorporating new parameters such as seat width.	Implemented most of them in the prototype (see 6.1)
	• The adjustability of the wheelchair should allow quick and convenient modifications without requiring return to the manufacturer or additional components.	Tested with the users and developed improvement proposals (see 5.2 &6.3)
Manufacture and costs	• The manufacturing process should be as short as possible to avoid long waiting time for players. • The cost of the wheelchair must match the price positioning of the corresponding product range in the market to ensure commercial viability.	Hypothetic advantages based on existing product information not yet verified (will be discussed in 6.5)

6.4 Future work

Not yet well explored

The final design of the seat width adjustment mechanism retains potential for further lightweight optimization without compromising rigidity. While a modest weight increase is acceptable, a lighter design may help expand the seat width adjustment function to a wider or more professional contexts.

Additionally, although the optimized handle , strap system, as well as asymmetric and inward-bending sideguards design schemes are relatively straightforward and have been partially reflected in the prototype, their functional effectiveness and user comfort have not yet been experimentally verified. Future work should include targeted prototyping and user testing to verify if these features really work for their target users.

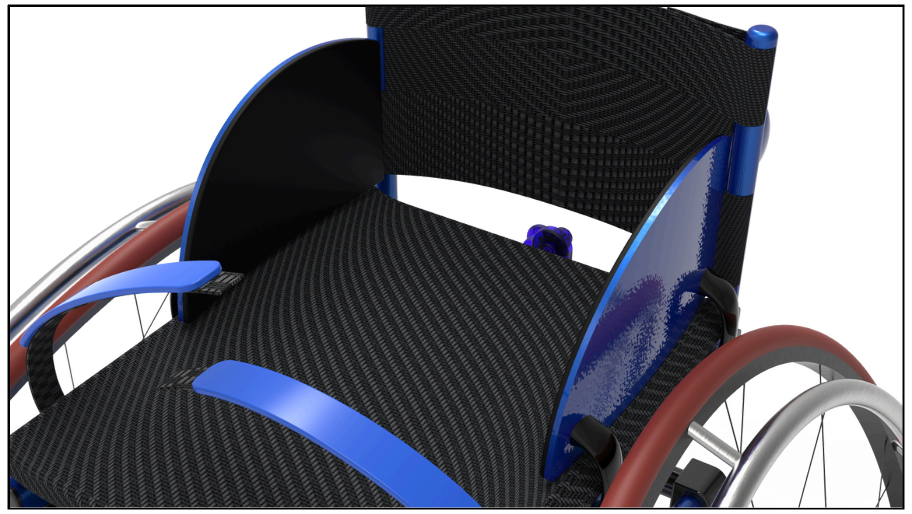


Figure 6.20 Straps and sideguards

Opportunity

An intriguing design opportunity was revealed during user testing but could not be pursued within the scope of this study. During the test users tend to have a tighter fitting with the adjusted seat width compare to their own wheelchair seat width. They noted that a tight seat width makes it difficult to get into the wheelchair, whereas post-seating seat width adjustment facilitates easier entry and enables a closer fit.

Based on this discovery, a seat width that can be relaxed in advance and quickly tightened after seated can be designed. It may only require changing the straps and sideguards (Figure 6.20) to achieve the function of loosening and tightening. This feature may appear simple and subtle, yet it could improve the fitting experience for players at different stages of development, as well as for the design of customized wheelchairs.

In addition, a wheelchair backrest design that mimics an ergonomic chair and provides sacral and lumbar support was also proposed as an option during the exploration process, but was not explored in depth due to limitations in the scale of the study. But it has the potential to avoid complicated width adjustments and make backrest angle and height adjustments more convenient.

Backrest adjustment to be settled

The backrest adjustment involve two parts, the upholsteries and the rods (Figure 6.21). The upholsteries uses a structure containing Velcro straps to achieve tightening at different widths. This design is feasible in concept and is supported by the existing wheelchair backrest structure (Figure 6.22), but a design that is sufficiently comfortable still requires further exploration and experimentation. Detailed information see Appendix J. The connecting rod part is designed with a partially overlapping structure and is fastened with screws and slots.

Rear wheel distance adjustment

To maintain a minimal gap between the rear wheel and the sideguard thus preserve the propulsion efficiency, the rear wheel distance should extend according to the seat width extension. The dual screw rod used in seat width adjustment mechanism could be an option (see Figure 6.23), but detailed design solution is still waiting to be proposed and verified in future work.

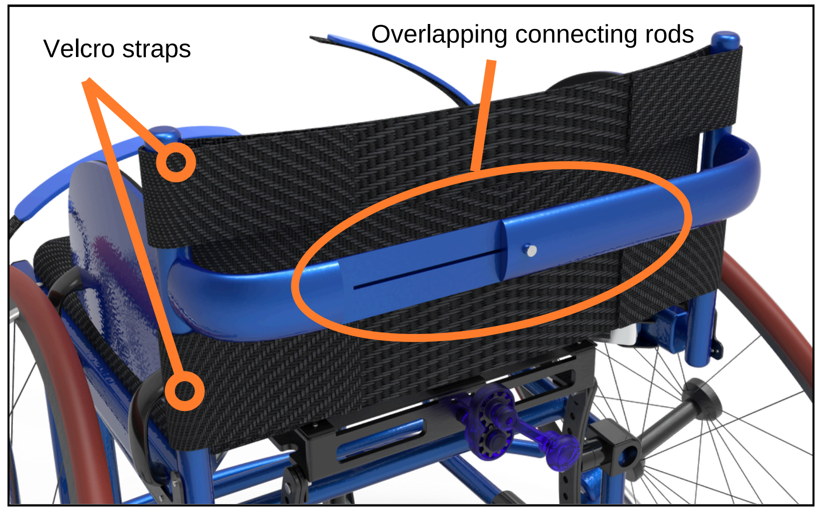


Figure 6.21 Upholsteries with Velcro straps and connecting rods with overlapping part fastened by screw and slot

Figure 6.22 Upholsteries with Velcro straps in existing wheelchair products

Figure 6.23 Dual thread lead screw rod used in seat width adjustment mechanism, able to perform dual extension

Manufacturing & business plan

Manufacturing

Materials

The main structural parts involved in the current design are all made of aluminum alloy, including but not limited to various frames and connecting rods. There may be a very small number of key connecting parts that need to be made of steel, while the handle and some connectors are made of plastic or nylon.

Means of manufacture

Based on the requirements of rapid prototyping, the screw connector in the prototype was made through PETG 3D printing, while the 4-bar connecting rods were produced via laser cutting and sheet metal bending (see Figure 6.24). However, since the structures are not complicated, both components could be adequately manufactured in metal through CNC. The handle and connector are currently also 3D printed in PETG, but can certainly be injection molded. The seat center frame can be produced by either sheet metal bending or welding, with the choice depending on specific practical requirements to be figured out later on.

Price

As the wheelchair with the most extensive adjustment functions, the price of the Top End Pro wheelchair is an important basis for estimating the price of wheelchairs with seat width adjustment function. Currently, it costs no less than 4,500 US dollars to customize a Top End Pro wheelchair, but for a Top End Sport BB wheelchair with just three sizes choices it costs only 3,500 US dollars. The framework structure of the two is the same, only the number of customization options is different. The latter has quite a price advantages among recreational wheelchairs, since **any wheelchair with customized seat width costs at least 1,000 US dollars more**. The wheelchair proposed in the design also comes in only three sizes: large, medium and small. Without considering the seat width adjustment structure, the cost is very similar to that of Top End Sport BB. Since the seat width adjustment structure uses cheap materials and the manufacturing process is not complicated, the estimated cost was around $350, with an estimated added price of less than $500, still maintain a certain price advantage (detailed estimation in Bottom-up method see Appendix Q).

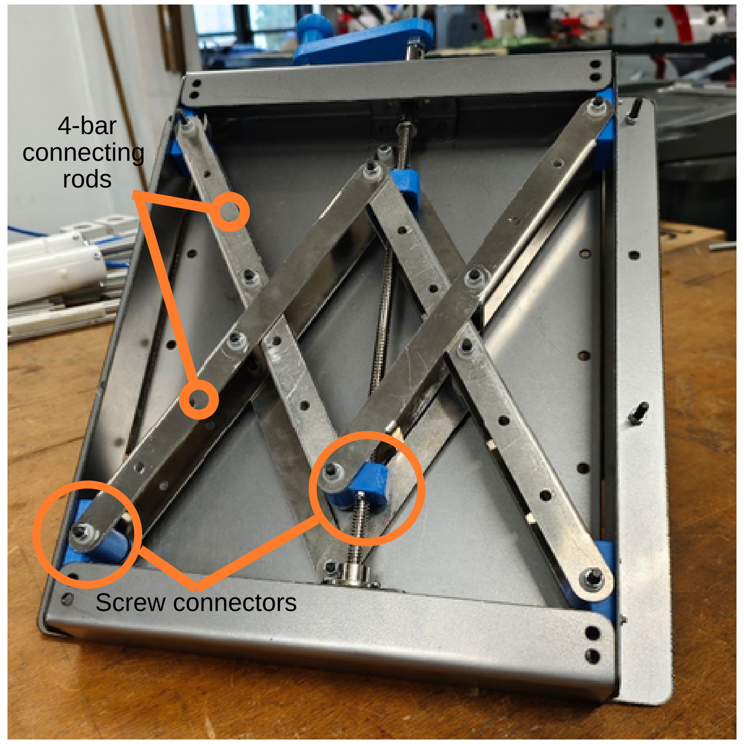


Figure 6.24 Seat frame part of the prototype

Hypothesis

Due to the increased use of standard components, like the frame, it is reasonable to assume that by saving the labor hours required for customization and pre-production, costs can be reduced, delivery speed can be increased, even enabling recycling industry.

Business plan

Market positioning

The market for basketball wheelchairs with adjustable seat widths is directly targeted at adolescent players in their physical developmental stages and those just starting out. Further expansion is the potential for them to serve as backup wheelchairs for clubs or rehabilitation institutions, providing opportunities for more people to join the sport and, to some extent, expanding the market. Ultimately, this feature is expected to be integrated into existing wheelchairs, enhancing their functionality and even expanding to other types of wheelchairs.

Teenagers & newcomers

For teenagers, wheelchairs with adjustable seat width frees them from enduring incompatibility due to changes in body dimensions, which can reduce their need for new wheelchairs, making it really competitive. For newcomers, this type of wheelchair can be used as their first wheelchair, and can be adjusted as their skills grow. When they enter the professional field, they can keep the wheelchair in the club to improve the cycle of shared wheelchairs.

Club & institution back up wheelchair

Furthermore, having a wheelchair like this available is a great option for clubs and rehabilitation institutions since they frequently accept newcomers or introduce people to the sports. Thanks to the adjustable seat width, it can be used as a spare wheelchair for a wide range of people who want to participate in the sport without having to worry about it not being fit. Apparently it works better than a used wheelchair without adjustable width.

Integrate to existing wheelchairs

After sufficient practice and development, this function can be integrated into existing wheelchairs to provide added value. The seat width adjustment function can increase the service lifespan of the basketball wheelchair and improve its adaptability over the lifecycle, which is valuable to governments, companies and clubs. Given its potential to reduce the number of wheelchairs that governments and foundations need to procure, the design is likely to gain policy or financial support.

Extend to a broader scope of sports wheelchair

Overall, the seat width adjustment function is novel for the entire wheelchair market. However, the demand for this function varies greatly in different scenarios. After fully developing the basketball wheelchair, we can explore other wheelchair markets with common seat width variations or sharing phenomenon, and quickly transfer the experience and results gained from the basketball wheelchair.

Me trying a spare wheelchair at BS Leiden

07 Conclusion

7.1 Conclusion

In conclusion, this thesis emphasis the importance of seat width fitting in recreational wheelchair basketball context, and proposes a novel improvement in basketball wheelchair design by integrating a quick and convenient seat width adjustment function with existing adjustable dimensions.

Overall, it helps to fill the gap in research and design of basketball wheelchair seat width adjustment. The seat width adjustment design enhance the wheelchair's ability to maintain a high level of fit for both the changing physical conditions of a single user and the needs of different users.

The design achieved seat width adjustment by applying screw drive and Scott-Russell mechanism, and its ability to adjust to a high level of seat width fit has been verified through user testing.

In addition, based on the user testing results, further design proposals were developed for other features associated with seat width adjustment.

By introducing seat width adjustment, Fitconnect not only better connect users to their wheelchair seats, but also enhances the user's connection to the community, and may encourage broader participation in wheelchair basketball.

7.2 Discussion

For manufacturing and opportunities see chapter 6.4. Due to time and capacity constraints, there are still many things worth exploring that have not been realized.

Research recommendations

In addition to the limitations mentioned in chapter 5.2, there are some research questions that could not be further explored and verified within the scope of this thesis.

The variation in seat width preferences for individual players has not been adequately explored. Further refinement of the variations in seat width preferences due to overeating, personal habit or weight loss mentioned in the survey could yield interesting results.

Testing recommendations

As mentioned in chapter 4.2, the sliding-guide seat width adjustment design was ultimately abandoned, but the specific cause of its blockage was not well analyzed or explored in depth. If time and technology permit, perhaps the problem can be further identified and made this design direction possible. Its advantage is that it is simpler and lighter than the existing four-bar structure.

Also as mentioned in chapter 5.2, the strength and safety of the structure and function in actual wheelchair basketball competitions have not yet been fully tested. If possible, the prototype can be further iterated and put on the court for actual testing.

Design recommendations

Another insight gained from the user test is that wheelchair basketball players value highly on their independence. They appreciate adjustment steps that can be completed on their own, but many existing adjustment dimensions are difficult to achieve independently, for example, the current seat height and angle adjustment, center of gravity adjustment, etc. Therefore, exploring how to optimize the existing adjustment method so that it can be completed independently is also a recommended and effective design direction.

Meanwhile, when a wheelchair integrates more than ten adjustable dimensions, even if individual adjustments are simple, the overall adjustment process can become cumbersome. Being able to adjust closely related parts synchronously, such as seat, backrest width and rear wheel distance, together would significantly improve the user experience. Designing linkages or removable, quick-sync adjustment mechanisms could be innovative.

7.3 Reflection

Change of focus

In the original project brief, the title of this thesis was defined as 'Designing of a System to Increase Affordability of Recreational Basketball Wheelchair', aiming at making recreational basketball wheelchair cheaper and more affordable.

Therefore, the initial desktop research for the project was conducted with the goal of reducing costs. It was not until the field research that it was discovered that since most of the expenses were covered by the government or organizations, recreational wheelchair basketball players in the Netherlands did not care too much about the price of the wheelchairs. Instead, they were more concerned about the quality and fit of the wheelchairs.

Based on this discovery, I chose to shift the focus of the project from reducing costs to improving adjustability. This was not something that could be fully anticipated at the beginning of the project, but it was exciting to really delve into the user scenarios to discover the real needs. And interestingly, the increased adjustability is hypothesized to reduce costs by reducing the level of customization.

In fact, I often questioned whether the project I had chosen was appropriate or sufficiently meaningful. However, this experience demonstrated that shifting focus is acceptable and that a truly effective design direction will show up during the process.

Lost in the prototyping

I've designed a wheelchair in my bachelors' and I thought I'm equipped with sufficient engineering skills and visions. However it turns out not exactly the case in the prototyping process, and it longer time than I expected, almost 1 and a half month delay until I figured out something that really works in the user test.

I had trouble identifying and evaluating design choices when applied in the real world, and found it rather hard to take the knowledge suggested by the supervisory team.

First of all, this dilemma is related to inefficient communication. I failed to reflect on my communication process in a timely manner. Reviewing through recordings is a very effective method, but it is a pity that I did not use it earlier. Second, my preparation for project-related knowledge is actually not sufficient. I should obviously take some elective courses related to actual engineering practice to be more prepared for prototyping. At the same time, although I have learned a lot in this process, there is still room for further improvement in the learning efficiency of the prototyping process. Thirdly, I think the knowledge and way of design thinking I gained in my bachelor are indeed different from the needs of my master's graduation project. The means and resources available for prototyping is quite different too, for example in China there is a diverse supply of hardware and semi-finished parts available.

Killing alternatives too early

One important thing I learned during this process is to always have multiple options, always have plan A, B and C. Because there are always things that don't work or can't be obtained in time.

Unfortunately, the design process still sometimes seems too linear, due to my repeated mistakes of killing alternatives too early. Many options are killed without being fully explored and researched. However, when the previous choice does not work, I often have to reconsider the options that have been eliminated.

Similar to the previous section, a lack of engineering knowledge and experience was a contributing factor to this problem. Furthermore, due to the project running ahead of schedule, I focused too much on time and neglected careful consideration during the prototype process, creating a vicious cycle. It wasn't that I lacked a diverse range of perspectives, but rather my lack of knowledge and my impatience under the current circumstances led to this error.

For similar situations in the future, better planning and reserves, and a calmer mindset will be helpful.

Personal learning goals

My initial design goal was to design something that wheelchair users could actually enjoy. The moment I saw their joyful face during the test the whole journey is worthwhile.

Also especially during the prototyping process I encountered quite a lot of engineering problem and gained different kind of knowledges on my way dealing with them. Although I still came up with some poor design solutions, I also gained invaluable knowledge about 3D printing, sheet metal bending, strength verification, different kind of mechanism, as well as the nasty friction.

Last but not least, I wanted to design something I could be proud of and could make a real difference. I don't think it will ever make it into production, but the results will undoubtedly be beneficial for recreational wheelchair basketball players, and I have no regrets about that.

General feedback

It was a long journey especially for an inexperienced designer like me, but I was also super lucky to have really nice supervisors, faculty staff, student assistants as well as friends and participants to help me all the way. I have grown tremendously as a designer in every aspect.

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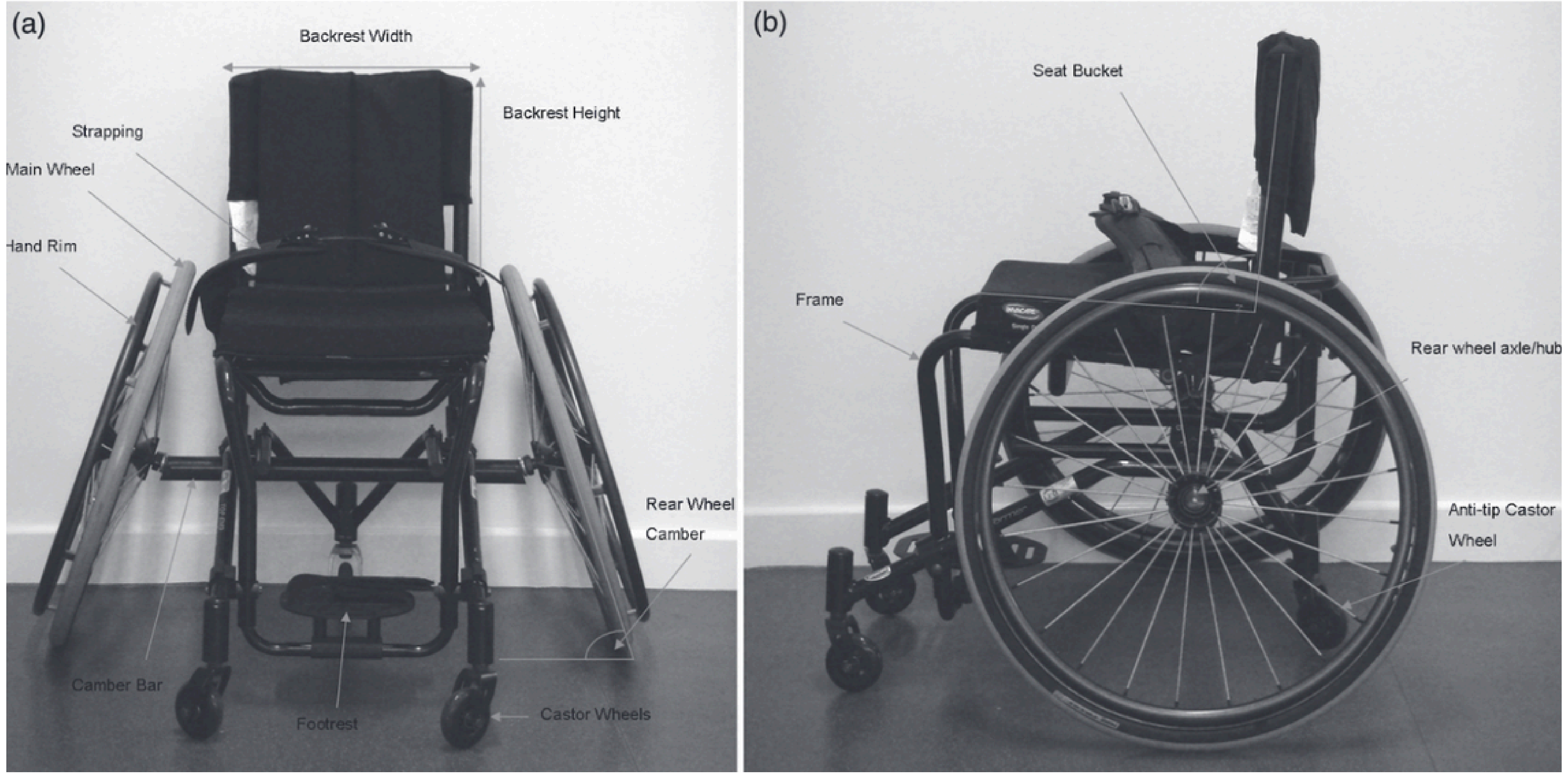
Figure 6.24: Prototype, Own Photograph

9 Appendix A

Literature review settings

This review focusing on the configuration of basketball wheelchairs, with the goal of uncovering design opportunities while building foundational knowledge and understanding. This review collects literature that presents evidence about the effects of wheelchair configuration on the mobility performance and physiological demand specific to wheelchair basketball, clarifies the direction and possibilities for optimization of partial configurations. It also reveals how most of the optimal configuration varies greatly from person to person, highlighting the significance of adjustable and customized designs. In summary, this review provides a basis and foundation for the future design project.

The literature search was primarily conducted based on Scopus databases as well as supplemented by Google Scholar, searching for keywords constructed around wheelchair basketball, also using adaptive sports and wheelchair innovation. Other secondary terms (performance, wheel size, camber, configuration, mass) were used alone and in combination with keywords.



Articles were included on the principle that they could be applied to the wheelchair basketball scenario, and the vast majority of the articles were specifically wheelchair basketball based, but some sports wheelchair content was also covered. The excavated articles categorized according to the parts of the wheelchair they addressed like the general weight, the wheel size, hand rim or the camber, also can be found in the Figure.

B. Mason, Porcellato, et al. (2010) conducted a qualitative examination and found the feedback from the participants used for identifying optimal settings were extremely subjective. Athletes have really different preferences for wheel size, camber and all the configuration elements. In this case a number of these studies were inconclusive or had limited results, but also generated many useful ideas and directions for expansion.

IWBF Rules on Configurations

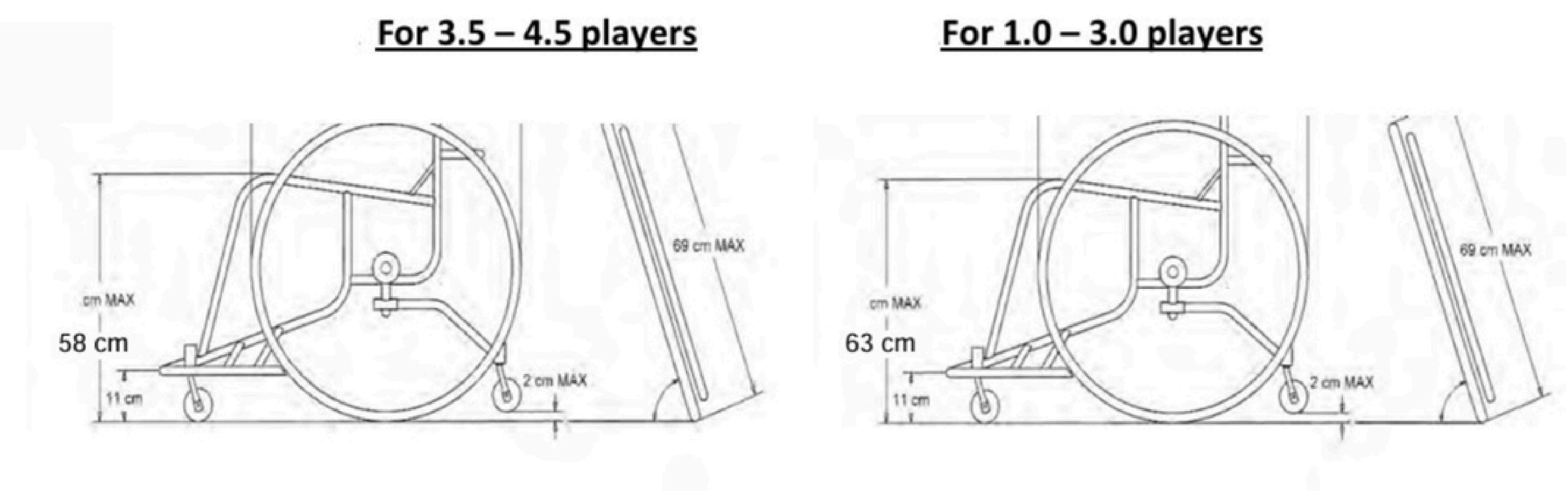
According to the IWBF (International wheelchair basketball Federation) official rules, the basketball wheelchair is regarded as an extension of the player, and must strictly adhere to specified configuration regulations to be eligible for competitive play. These requirements may give way a little bit in recreational scenarios, but they should still be consistent in principle.

Here are the essential requirements mentioned in the rules. Primely players are classified into different classification points according to their level of disability and mobility, which may range from 1.0 to 4.5. And the seat height, measured with front castors in the forward driving position and the player removed, must not exceed: 63 cm for classification points 1.0 – 3.0 and 58 cm for classification points 3.5 – 4.5, cushion included.

Anti-tip castors positioned at the rear of the wheelchair must remain within the width defined by the inner edges of the two main wheels and not protrude beyond the vertical plane touching the rearmost points of the drive wheels with a maximum clearance of 2 cm from the playing surface. Armrests and upper body supports affixed to the wheelchair must not extend beyond the player's natural body line, specifically the legs or torso when seated in a neutral position.

The horizontal bar at the rear of the backrest must be padded with material at least 1.5 cm (15 mm) thick. The padding must be sufficiently flexible to allow an indentation of up to one-third of its original thickness under applied pressure. Also not exceed an indentation of 50% of its original thickness under sudden force. These specifications are in place to minimize injury risk to other players during contact.

Additionally, the cylinder principle may have impact on the wheelchair configurations. It is defined as the space within an imaginary cylinder occupied by a player and his/her wheelchair on the floor and includes the space above. This indirectly emphasizes the importance of legroom, and the requirement to ensure adequate legroom allows the player to remain within the cylinder.



In all cases the height is measured from the floor to the highest point on the seat platform including the cushion if one is used.

9 Appendix C

Players classification

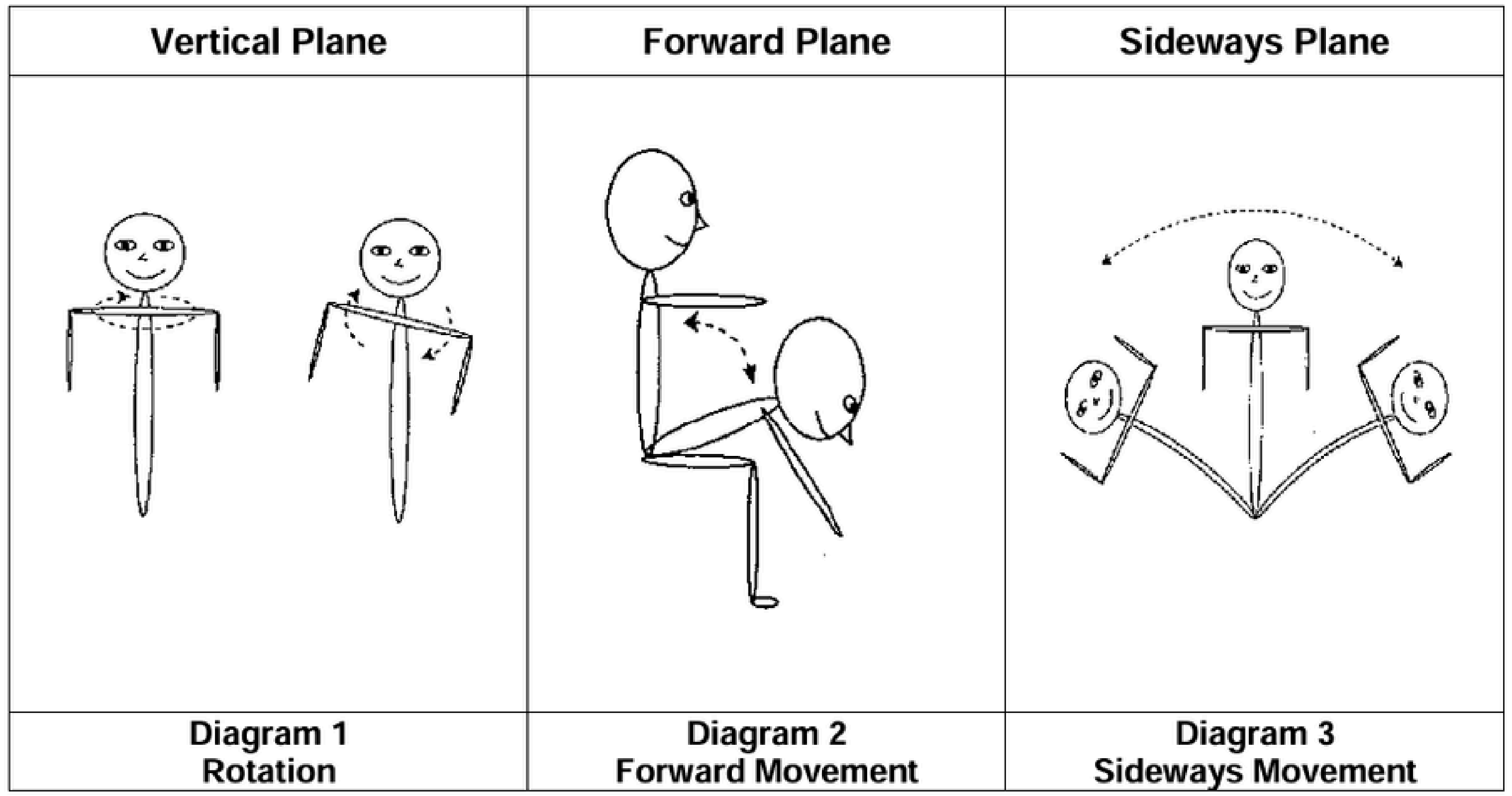
According to the International Wheelchair Basketball Federation (IWBF), athletes must have an eligible impairment—include impaired muscle power, reduced range of movement, limb deficiency, leg length difference, hypertonia, ataxia, or athetosis—and also meet the sport's minimum impairment criteria (MIC) in order to compete internationally. The latter means that the player's leg muscles must have a part of their motor function that cannot work against gravity.

Most wheelchair basketball players have the above-mentioned eligible impairment. However in recreational context, players with higher muscle motor function who do not meet the MIC requirements also actively participate. And sometimes able-bodied participants may also be involved in wheelchair basketball in order to make up the team size.
Accounting for the vast differences in disabilities and motor functions among players, wheelchair basketball uses a classification system to promote fairness in the competition. Players are divided into classification of 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 and 4.5 points, as recorded on the ID card, and the assigned value may be adjusted during the tournament until the play-off round. And in one team the combined classification score of all players on court must not exceed 14 points.

The key element of classification is the observation and assessment of each player's volume of action.

The volume of action describes the extent to which a player can move the trunk in different directions and return to an upright seated position without external support. It includes movements in three planes shown in Figure X: the vertical plane (trunk rotation left or right), the forward plane (bending forward and returning upright), and the sideways plane (leaning left or right).

- Class 1.0: Players have no active trunk rotation, little or no forward control, no sideways control, and must rely on their arms to regain balance.
- Class 2.0: Players have upper trunk rotation and partial forward control, but lack lower trunk rotation and sideways control.
- Class 3.0: Players have full trunk rotation and forward control, but no controlled sideways movement.
- Class 4.0: Players have full trunk rotation and forward control, with controlled movement to one side but limited control to the other.
- Class 4.5: Players have complete trunk movement in all directions, including vertical, forward, and sideways planes.



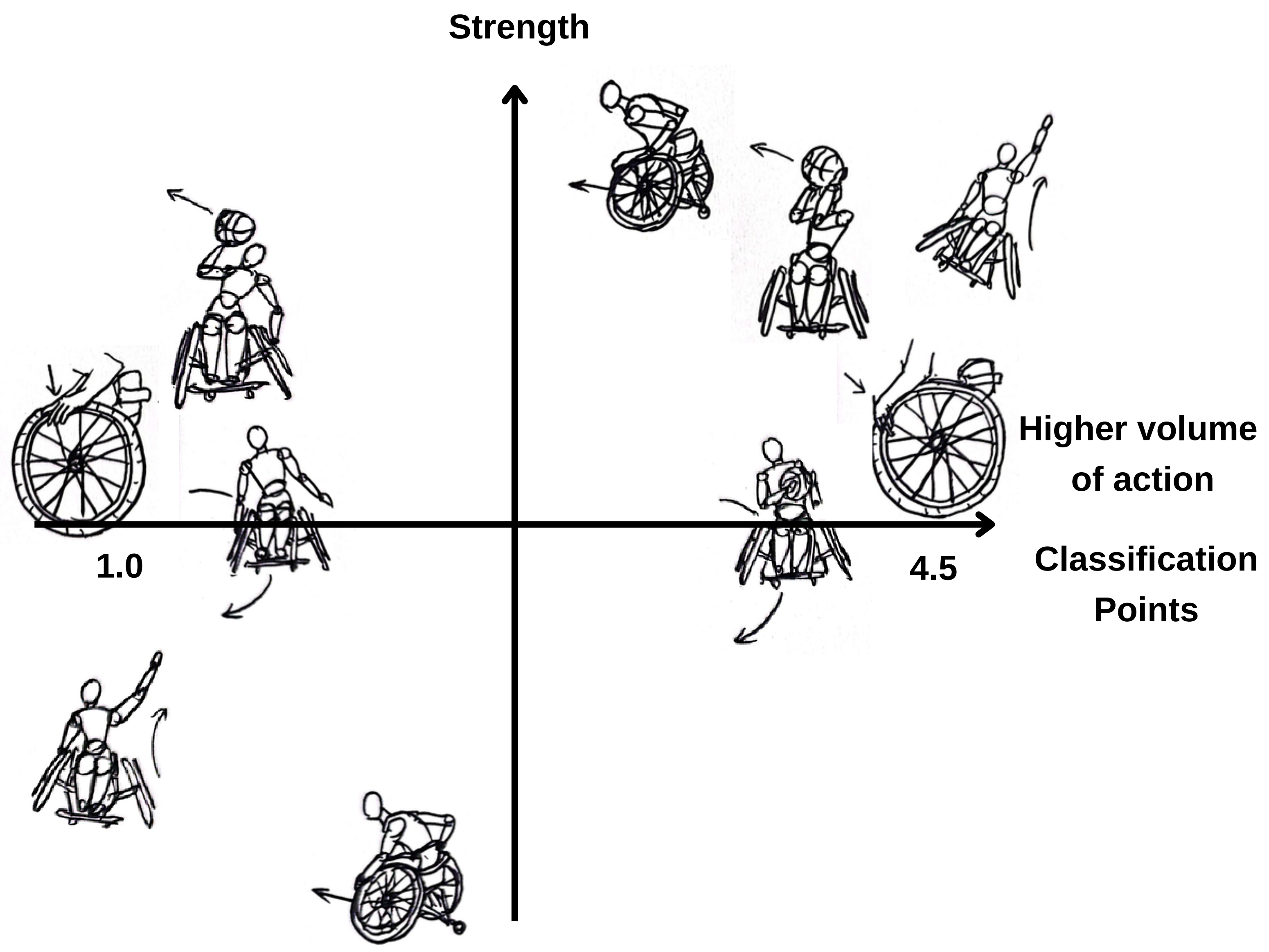
Motion observation combines

Observations of this team's player movement and confirmations with players and coaches provided new insights into player characteristics and preferences. Also forms an effective contrast with the classification system. In general players of different mobilities, skill levels and strengths drive their wheelchairs and play differently and thus have different demands on their wheelchair settings. These three dimensions are highly correlated but not exactly equivalent, so the subjective initial assumption of distribution is obtained as shown in Figure 2.14.

During straight-line movement, stronger players with better skills will drive the wheelchair with both arms synchronized, while players with relatively less strength will drive with alternating arms. In addition to strength, the level of disability and the mobility it results in also affects the way players play the game. When steering at certain speeds, players with higher volume of action can steer without touching the hand rim, accomplishing the steering through upper body movements alone, while players with slightly less experience and mobility need to control at least the hand rim on the steering side.

Players with lower levels of disability who are more athletic and have higher scores in classification are able to utilize lower back strength to support throwing and blocking motions, and the position of the gripping hand rim when bending forward is shifted to the front. In contrast, players with limited athleticism and higher levels of disability had lower scores and could only rely on extra arm movements, such as throwing a one-armed pitch with a backward tilt, and the position of the gripping hand hub was fixed in an upward position. Also, they must carefully striking their balance by making relatively large swings of the upper body.

These motion patterns make the level of wheelchair fit required by players with different levels of strength, disability and skill varies. Players with more strength and larger volume of action require a higher degree of seat fit, with a very tight fit at the hip position to ensure that upper body movements reach the wheelchair in a timely manner. This also matches the previous analysis about existing products.



Sketches showing players' different driving wheelchairs and playing styles

9 Appendix E

Further Comparison

As a comparison to the previous chapters, the Miami Heat wheelchair basketball team is revealed in the public service documentary movie called The Rebound. Miami Heat is also a small team of around 20 people but a full-time professional teams play in national competitions in America. They are in quite a different situation than the more recreational BS Leiden Rollers.

They train at greater intensities throughout the day, generating far more crashes and travel speeds than is the case in Leighton, and take their basketball wheelchairs off the field to train on roads or in parks, dramatically increasing the rate of wear and tear on the wheelchairs. They need a lot of extra funding to cover the cost of traveling to the nationals, as well as replacing necessary parts like rims, spokes and tires. In the movie they had to go into the car wash business to raise money.

While the Miami Heat show a very typical situation for a professional team, the situation faced by recreational players in other countries, especially in developing countries, can be even more dire. While official teams are usually supported by the government, recreational players are often left paying the majority of the price of a basketball wheelchair, making the expensive price their main dilemma.

9 Appendix F

Other concepts alternatives

Here are some other ideas that came up during the brainstorming process that were not further explored.

Side guard addition

It is an extension of the side support that appears in the user context, and a variant of the first solution, namely a custom 3D printed add-on mounted to the wheelchair seat based on the problem of the existing wheelchair. The scale is smaller and the scope of the problem solving is also smaller, but there are similar cost and speed advantages.

Stretchable seat

Inspired by child safety seats retrofitted to cars, the sides and back are stretchable to accommodate different body sizes. However, there is less range that can be accommodated and more components to add.

Carbon Fiber Customized

Inspired by prosthesis receiving chamber and the Formula 1 racing seat making process, a carbon fiber seat is stripped from the human body to create a perfect fit and then retrofitted to the wheelchair frame. It is more suitable for professional racing situations than recreational context, and is way too costly in terms of labor and technology.

(a)

(b)

(c)

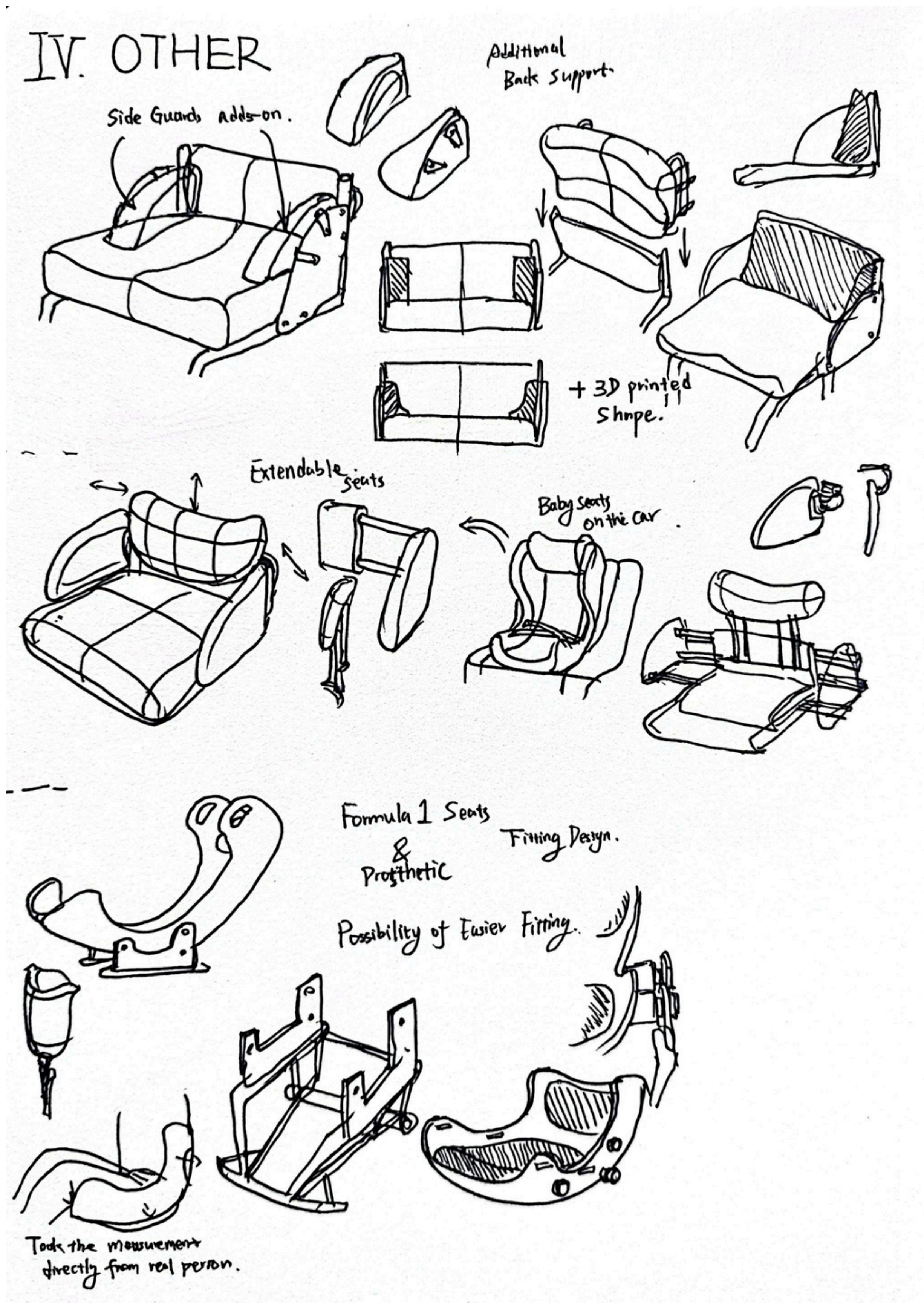


Figure Sketches of Side guard addition (a), Stretchable seat (b) and Carbon Fiber Customized (c)

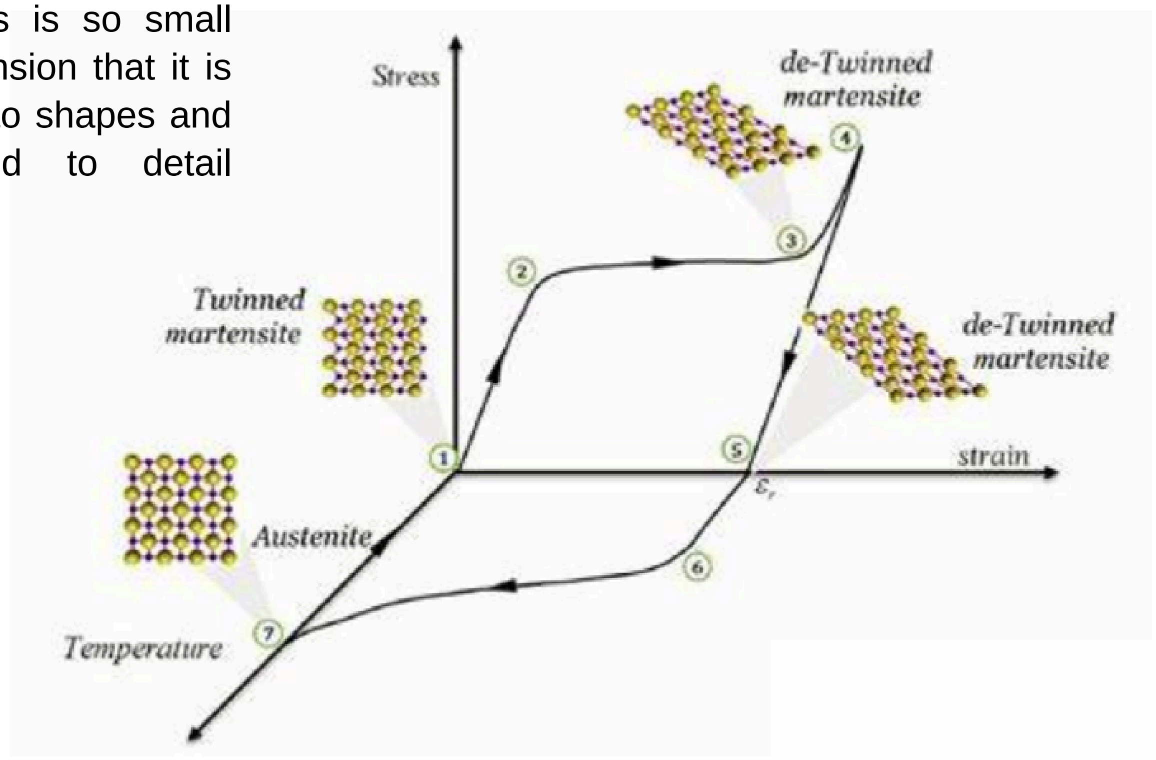
Appendix G

Technology exploration

Shape morphing materials

Considering the changing fitting requirements, accommodating shape morphing materials may be one of the solutions to meet the needs.

Electrically deformable polymeric materials such as graphene composite films can shrink and deform when electrically energized, but it is not practical to keep them energized in a wheelchair. Shape memory alloys or polyether-based materials that can be heat molded can be deformed under the influence of thermodynamics, while at the low-temperature state the shape can be maintained. However, the range of deformation of such materials is so small compared to the human dimension that it is difficult to apply them directly to shapes and more likely to be applied to detail components.

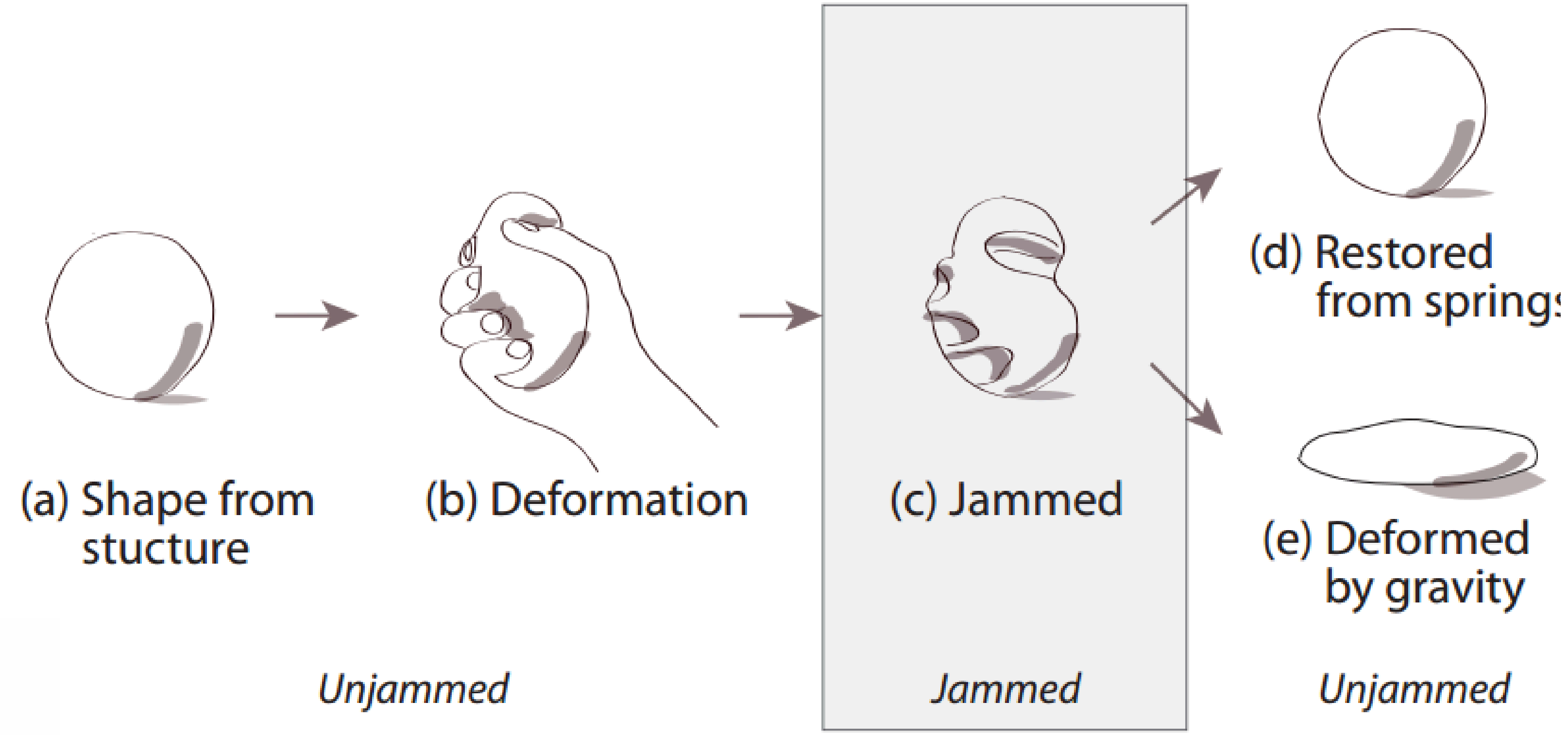


Indication of theoretical background of Shape Memory Alloys

Particle jamming

Particle jamming is an effective technique for creating flexible, shape-adaptive interfaces by controlling material stiffness. It exploits the transition of particulate media from a fluid-like to a solid-like state by modulating interstitial air pressure—flowing freely with excess air and becoming rigid under vacuum-induced compaction.

While this technique demonstrates promising potential for rapid fitting, the limited number of practical applications makes it difficult to assess the impact resistance of particle-jammed structures in the context of wheelchair basketball.



Example of jamming techniques enables new possibilities for shape state transitions

9 Appendix H

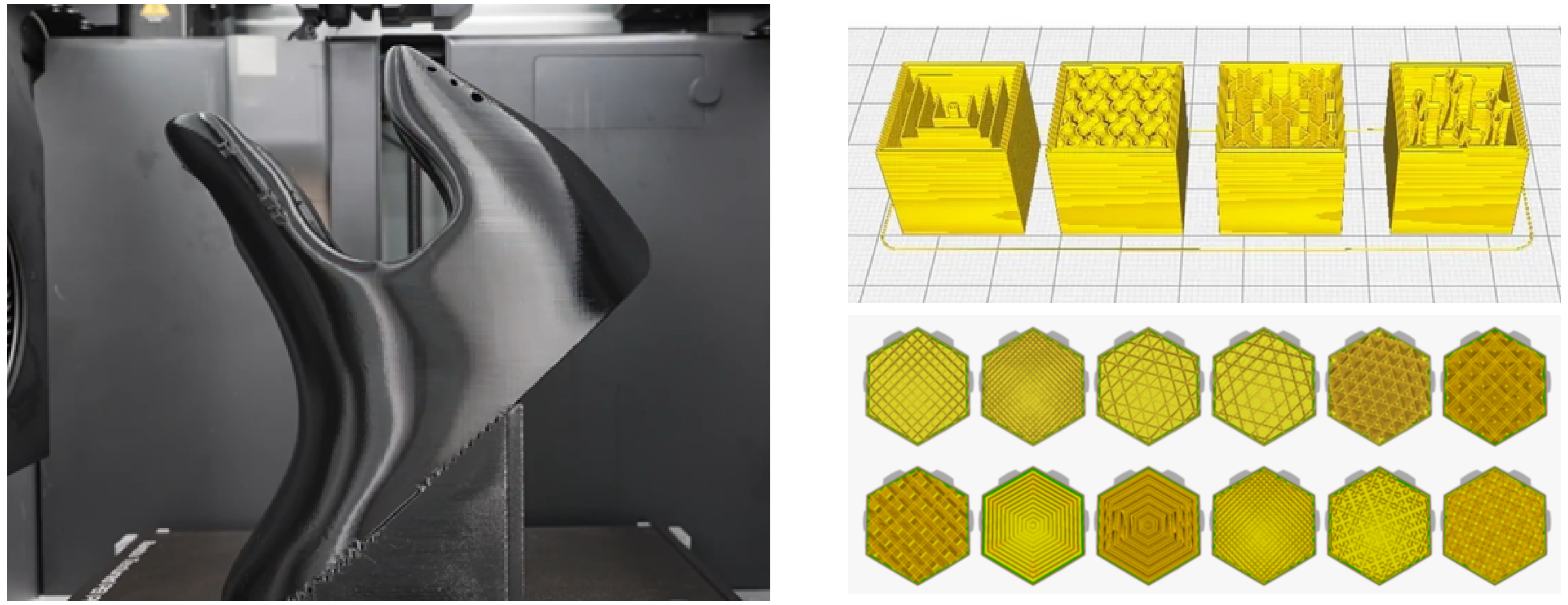
Exploring 3D Printing

3D printing has the potential to combine customization with rapid advanced production. There are already many applications for 3D printing cushions and other items that fit the human body's curves, like the wheelchair cushion. The sneakers are an example of technology enabling rapid design and production, with customized shoes being produced in a day.

Even more promising for this project is the fact that the same material can be adjusted to be soft and hard to the touch by varying the infill pattern, allowing the printed product to both fit the body to ensure comfort and provide support, such as the foot prosthesis shown in the bottom right figure.

3D Printed wheelchair cushion aiming for breathability

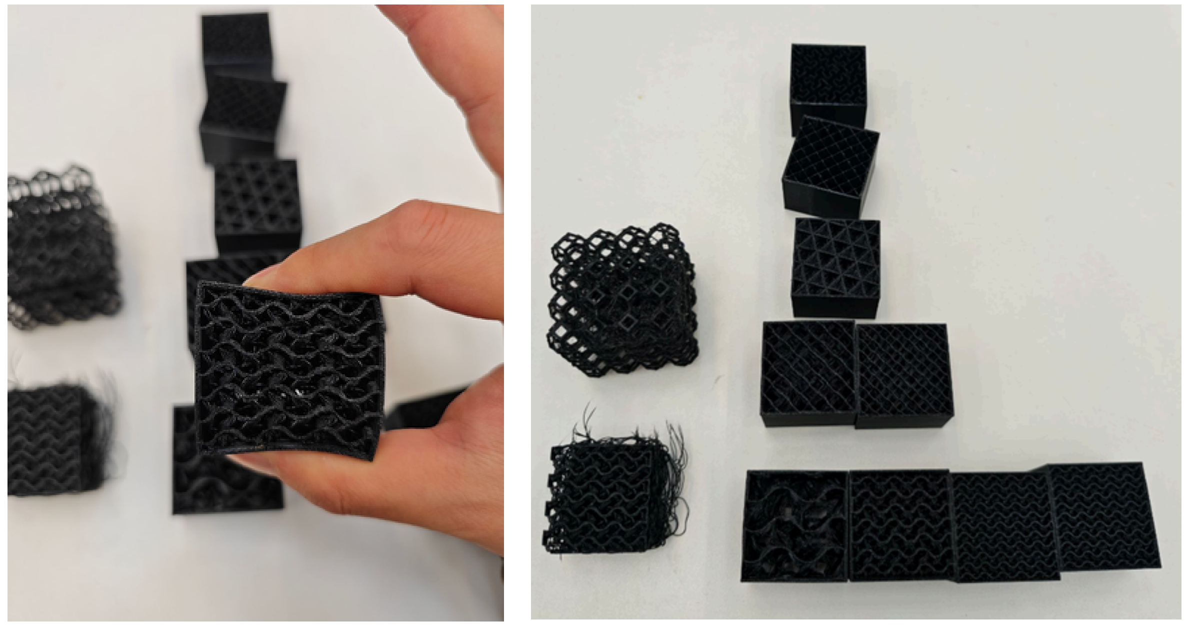
3D Printed sneaker from 3D printing company Zellerfeld



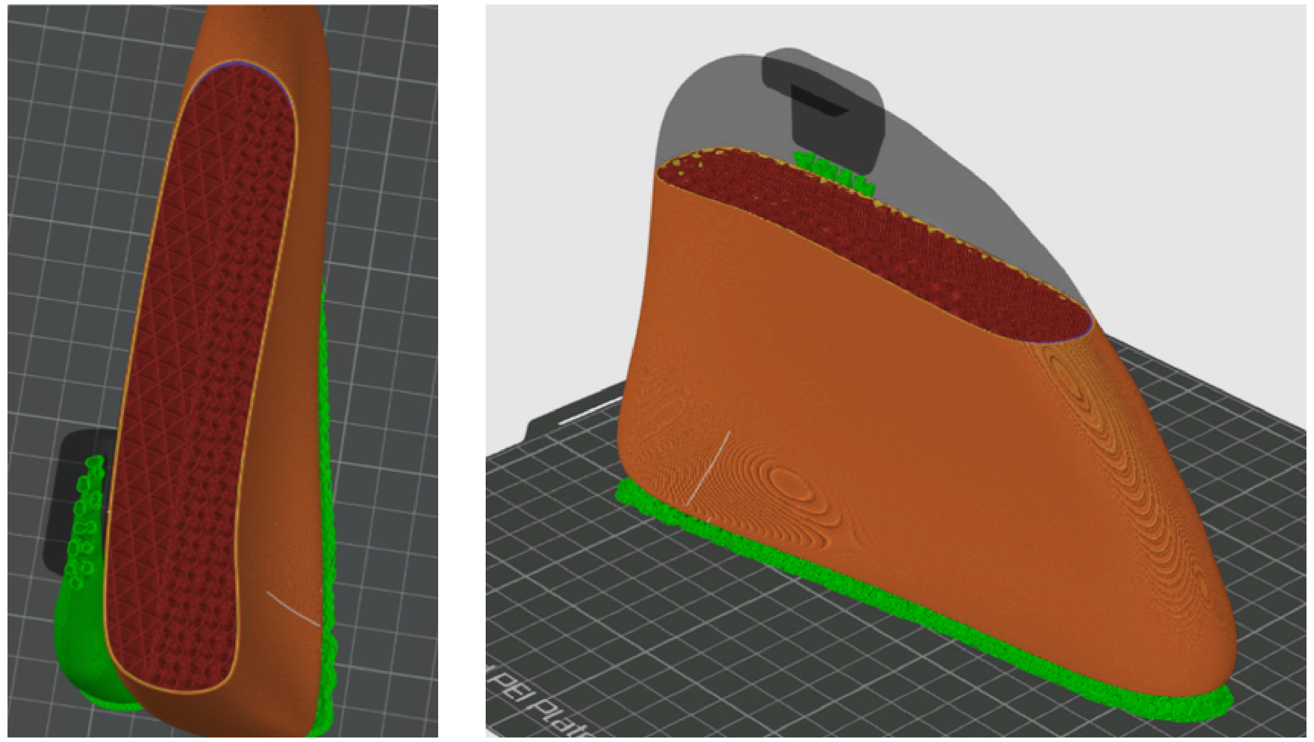
3D Printed foot prosthesis using different infill patterns in one material

9 Appendix H
Exploring 3D Printing

After further research and discussion, the shortcomings of 3D printing large items began to gradually reveal itself. Printing the entire wheelchair seat as a single 3D-printed piece turns out facing several difficulties, such as the need for a large printer, relatively long production time, high material use, and problems with strength, surface quality, and later repair. Because of these challenges, the approach was adjusted to print only selected key components, for example sideguards and the cushion. The rest of the seat can be made with conventional methods and adjustable structure, while 3D-printed piece can be used to add most comfort on those place with direct contact to human body.



Test of different infill patterns and wall thickness



Sliced sideguard model in Bamboo Studio
with different infill patterns on different side

Several models were printed to justify the infill patterns functionality mentioned in the concept design phase. A pair of 1:2 sideguard was printed in TPU with a bit lower density gyroid on the inner side and higher density cubic outside. The touch of its inner side is slightly harder than that of ordinary seat cushion sponge, which can effectively reduce the pressure on the skin surface while maintaining the shape. At the same time, its shape that conforms to the curves of the human body can also improve perceived comfort. Overall, this model shows an advantage in comfort when attach to the hip side compared with the flat wooden board and the hard curved sideguard printed with PLA.

Sideguard test model printed in TPU

9 Appendix I

Rice-vacuum-based particle jamming

For the instant shape morphing solution using particle jamming technique, simple simulation can be carried out with rice and small size vacuum storage bags. The rice is placed in a bag, shaped, and then vacuum-sealed so that the shape is maintained and hardened, following the same principle as particle jamming.

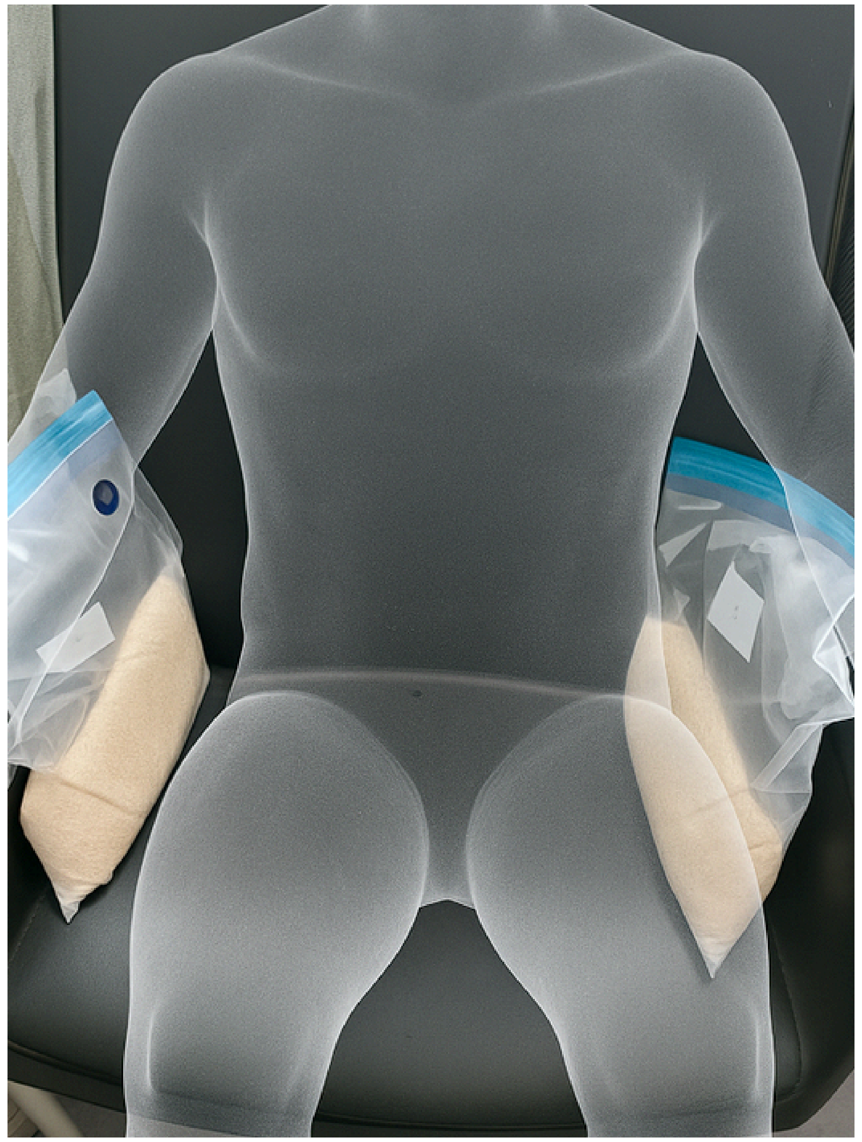
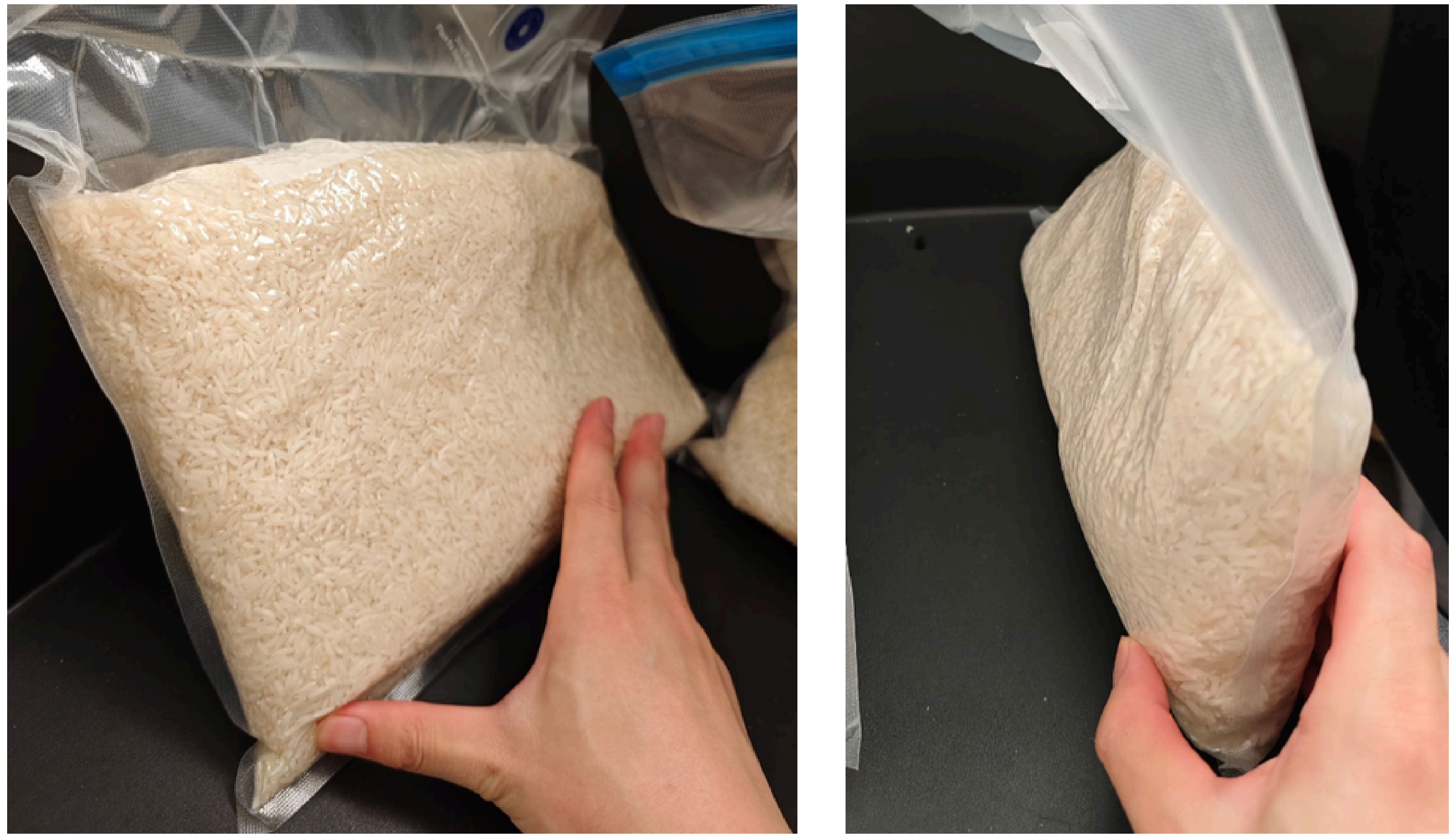


Diagram of user testing bag-based-sideguards filled with rice

As shown in the figure, according to the designed solution, the user sits between the bag-based-sideguards filled with rice, adjusts his posture and squeezes the bags, and the bags change shape and are gradually drawn into a vacuum. Ideally, this design would be able to adjust to the body's curves in real time while maintaining its shape for a relatively long time. Obviously, real time adjustment is its advantage, but many unexpected problems were encountered during the testing and exploration process.

Firstly, common particle jamming applications focus on the horizontal direction rather than the vertical direction.

When particle jamming happens in the vertical direction, the arc that should fit the curve of the human leg will become closer to a slope under the action of gravity and cannot truly fit the curve (as shown in figure). This situation greatly affects comfort and its range of adjustment. Secondly, the surface of jammed rice bags is really hard, contact with the skin may cause discomfort or even pain. This is due to the nature of the particle jamming, and even using particles more elastic than rice wouldn't change it much.



Particle jammed rice bags

Covering the surface with a sponge would avoid direct contact, but it would be more difficult to adjust its shape to fit the curves of the human body. Gravity, rather than surface pressure, would dominate, making it more like a slope. Thirdly, The strength after jamming was lower than expected with possibility of breaking it by hand, and it softened significantly after 2 hours. This is related to the vacuum equipment and the airtightness of the bag. However, considering the intense confrontation in wheelchair basketball, its strength and retention capacity are still a challenge.

Exploring back rest

In addition, the device also tests the interaction between the back rest rod distance and the seat width adjustment. Participants attempted torso lean back and arm swing in different backrest configurations. When the seat width changes and the back rest rod remains, it will affect the normal upper body backward movement, such as leaning back or stretching the arms. It is easy to conclude that the rod distance of existing two rod back rest should follow the seat width adjustment to ensure that basic movement is not restricted. A narrower integrated back rest can also solve this problem, but it is not used in basketball wheelchairs due to its limitation on leaning back dimension.

TPU sideguard performance





Back rest rod distance test

9 Appendix J

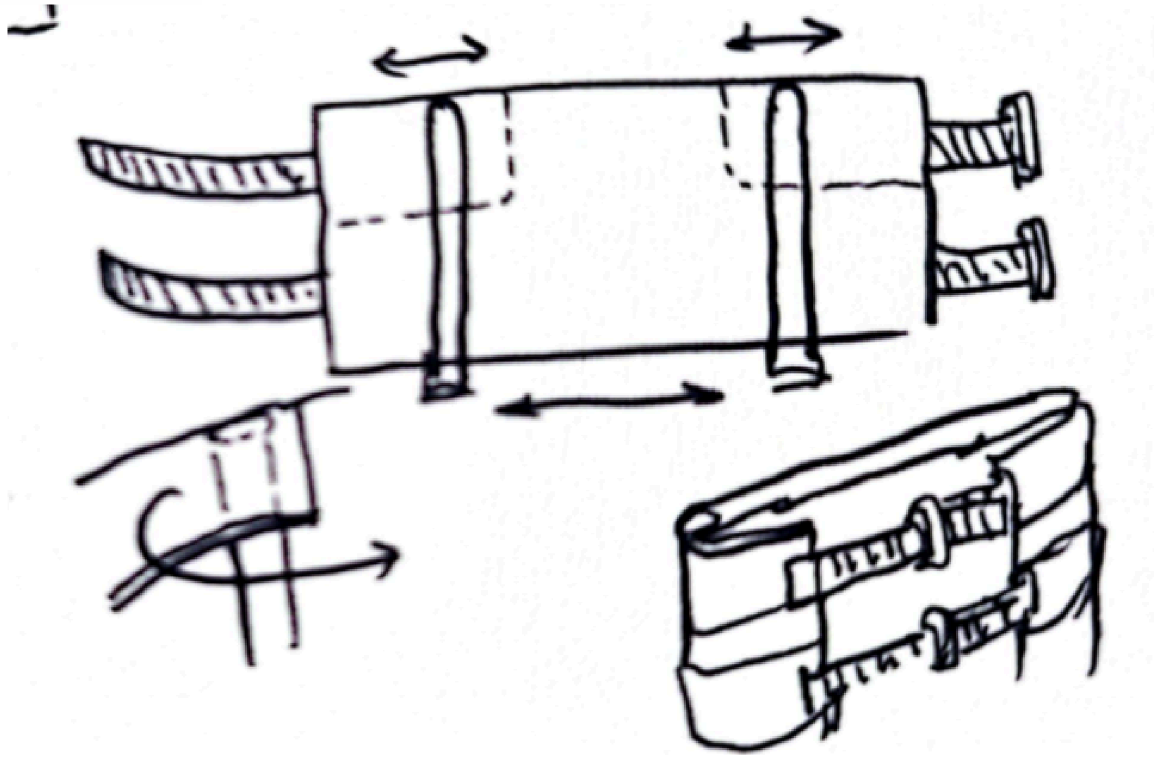
Exploring back rest

Back rest fitting

Previous studies have proved that the distance between the two rod backrests must be adjusted along with the seat width, so the back rest cushions also need to be adjusted to different widths. Fortunately, the existing customized wheelchair back rests have the function of adjusting different positions and shapes through magic straps (Figure 4.11), which can be converted and applied to the current situation.

Simply widen the connecting sleeve between the back rest and the rod to the width of the adjustment range, and then tighten the back rest with a sufficiently strong magic strap to achieve back rest adjustment under different width conditions.

Existing customized back rest with magic straps



Sketches of width adjustable back rest

Renderings of width adjustable back rest

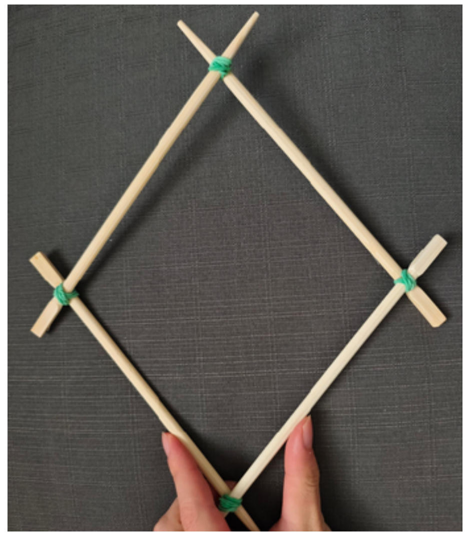
9 Appendix K

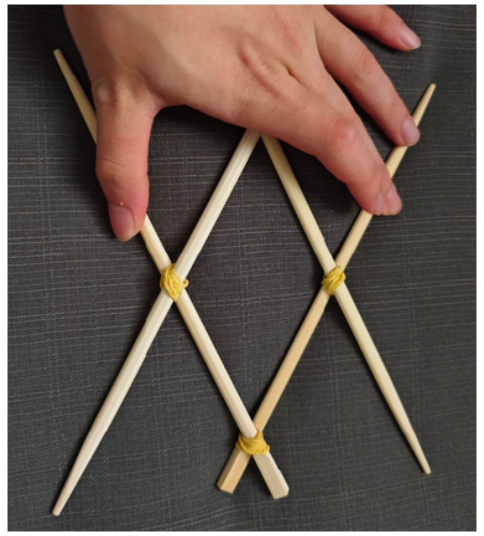
Exploring 4-bar mechanism

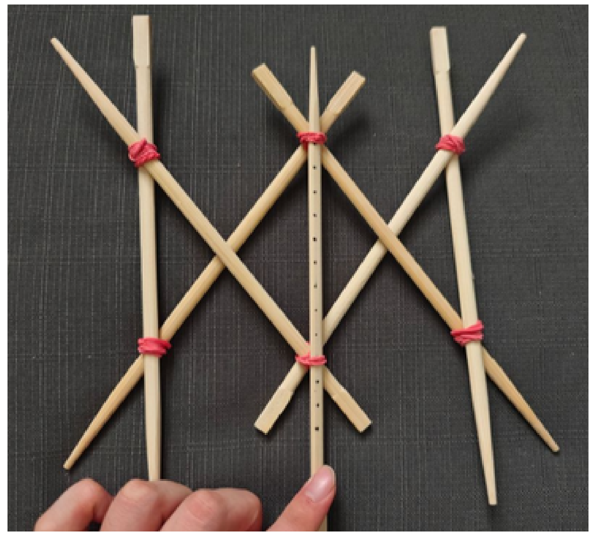
In order to explore the four-bar mechanism, existing applications including the structure of jacks and folding wheelchairs were referenced.

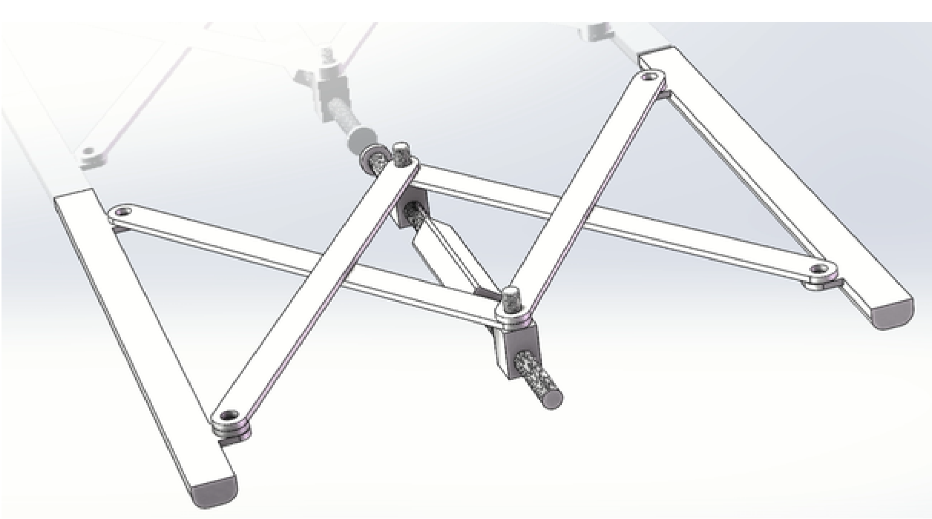
At the same time, rough prototypes were made using chopsticks and rubber bands, as well as sewn corrugated cardboard for testing.

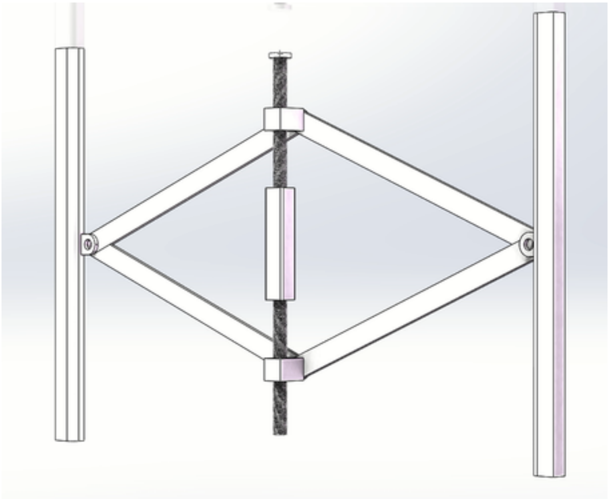
Based on the unstable performance during testing, Solidwork modeling was performed to verify the results, and ultimately a combination with a Scott-Russell mechanism was chosen to further constrain the movement.

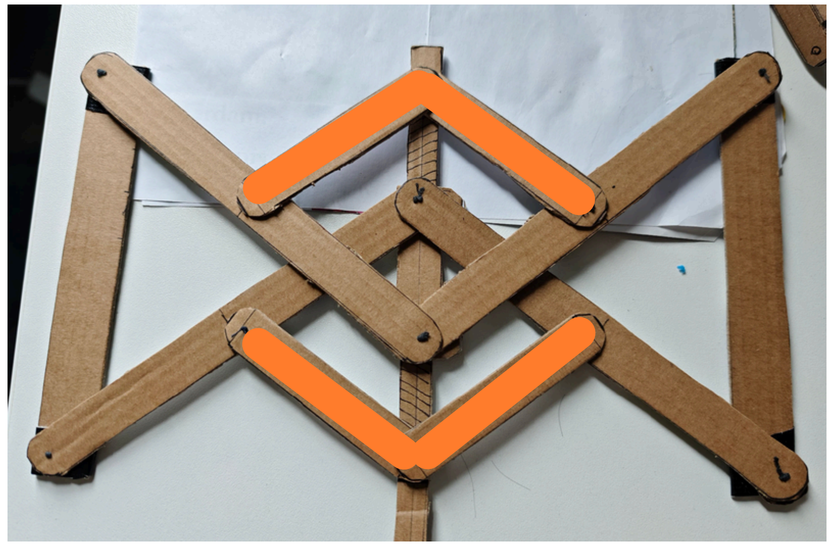


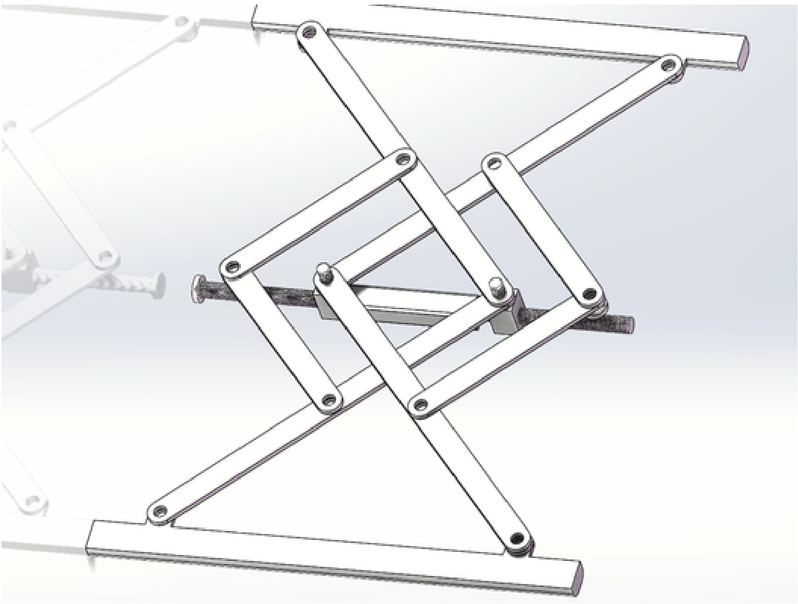


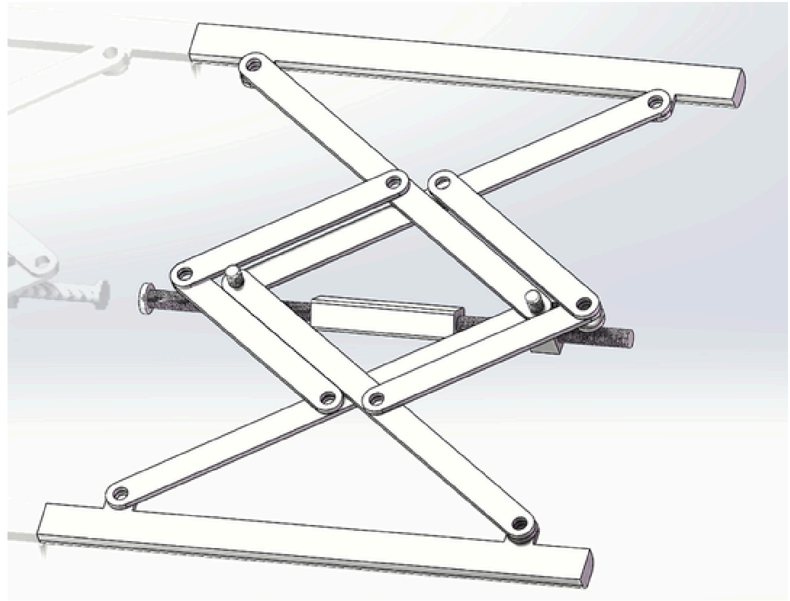












Appendix L

Research Survey

Test of basketball wheelchair seat width adjustment prototype

Which classification are you assigned to? (1.0-4.5) ____________

(Stationary stage)What do you think of the seat width fitting level?

	0	1	2	3	4	5	6	7	8	9	10	
perfect fit/ no discomfort	○	○	○	○	○	○	○	○	○	○	○	not fit/ max discomfort

(Moving stage)What do you think of the seat width fitting level?

	0	1	2	3	4	5	6	7	8	9	10	
perfect fit/ no discomfort	○	○	○	○	○	○	○	○	○	○	○	not fit/ max discomfort

How acceptable was the process of adjusting the seat width?

	0	1	2	3	4	5	6	7	8	9	10	
easy/ convenient	○	○	○	○	○	○	○	○	○	○	○	hard/ very inconvenient

How safe do you feel during the adjustment process?

	0	1	2	3	4	5	6	7	8	9	10	
safe/ nothing to worry	○	○	○	○	○	○	○	○	○	○	○	really worried/ not stable

Would you like to try different seat widths?

	0	1	2	3	4	5	6	7	8	9	10	
Yes and frequent	○	○	○	○	○	○	○	○	○	○	○	not at all

- What features or feelings about the adjustable seat width worked well for you?

____

- What problems did you notice, or what would you want changed?

____

- How does this seat width feel in comfort compared to your current chair?

____

- In your opinion, what benefits could adjustable seat width bring? (personal / community)

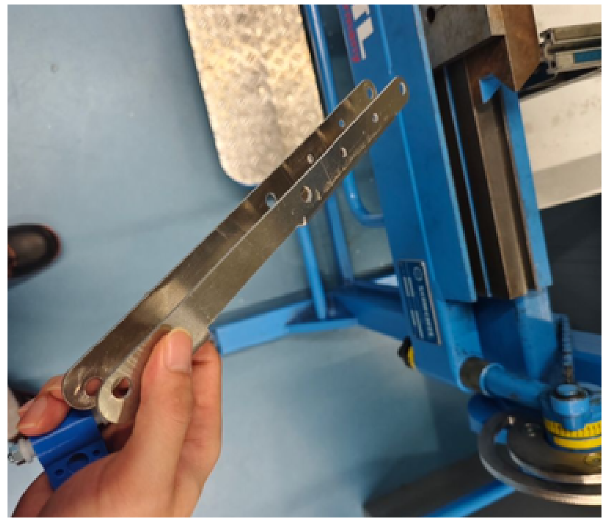
____

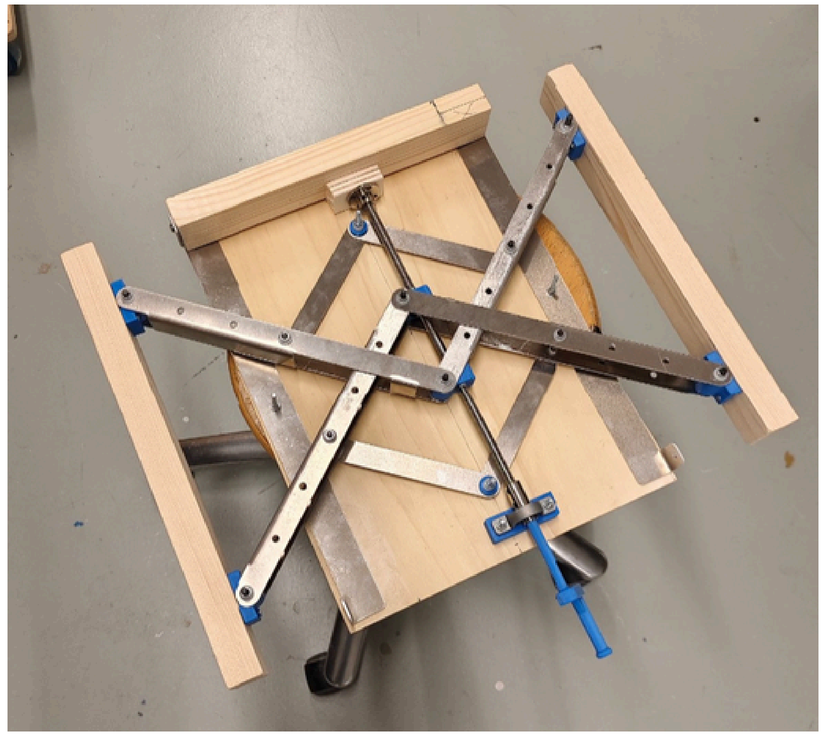
- Other feedback?

____

9 Appendix M

Final prototyping process










9 Appendix N

Test scene

9 Appendix N

Test scene



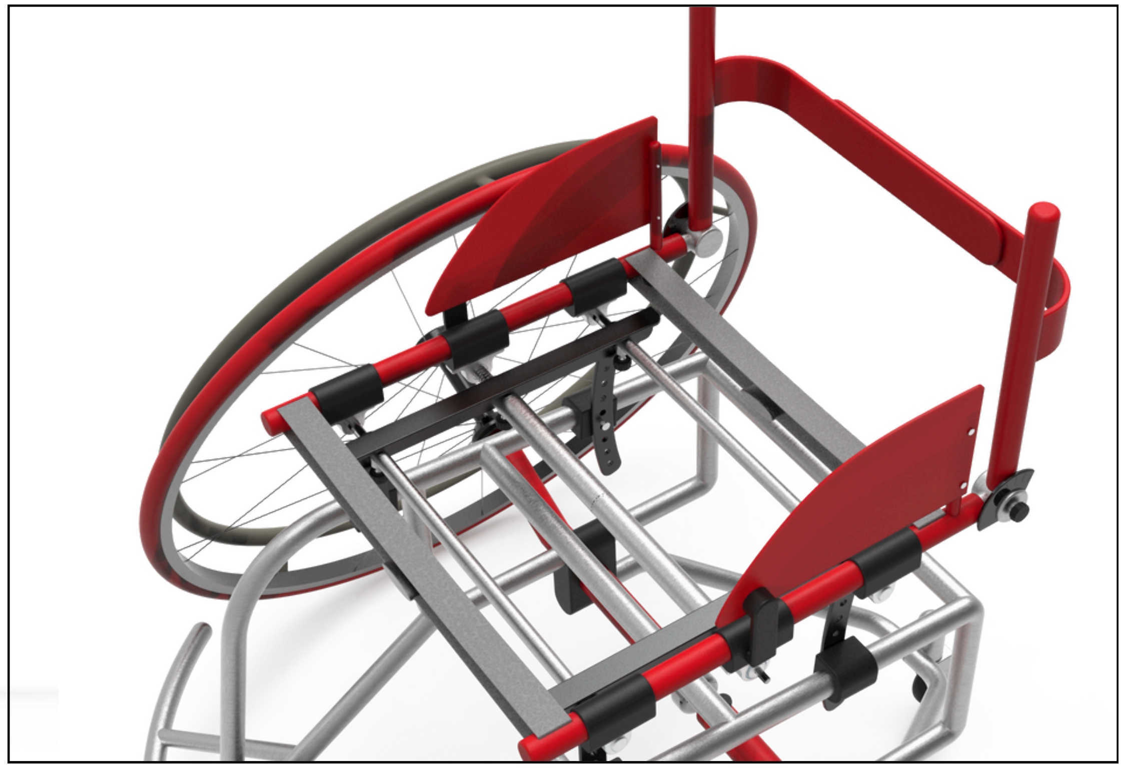







Rendering process

This was a design and rendering solution based on a sliding prototype, but was ultimately abandoned because feasibility issues were not fully resolved.



Test results

Research Survey
Test of basketball wheelchair seat width adjustment prototype

Which classification are you assigned to? (1.0-4.5) 3.5

(Stationary stage)What do you think of the seat width fitting level?
0 1 2 3 4 5 6 7 8 9 10 — perfect fit/ no discomfort … not fit/ max discomfort (marked: 2, 7)

(Moving stage)What do you think of the seat width fitting level?
0 1 2 3 4 5 6 7 8 9 10 — perfect fit/ no discomfort … not fit/ max discomfort (marked: 2)

How acceptable was the process of adjusting the seat width?
0 1 2 3 4 5 6 7 8 9 10 — easy/ convenient … hard/ very inconvenient (marked: 4)

How safe do you feel during the adjustment process?
0 1 2 3 4 5 6 7 8 9 10 — safe/ nothing to worry … really worried/ not stable (marked: 1)

Would you like to try different seat widths?
0 1 2 3 4 5 6 7 8 9 10 — Yes and frequent … not at all (marked: 3)

- What features or feelings about the adjustable seat width worked well for you? comfortable easy one hand. operation.
- What problems did you notice, or what would you want changed? smoother turning handle
- How does this seat width feel in comfort compared to your current chair? width is almost the same
- In your opinion, what benefits could adjustable seat width bring? (personal / community) body changes / 5 years for a chair is long
- Other feedback?

23/09/2025

36/36.

& should against the wall.

Research Survey
Test of basketball wheelchair seat width adjustment prototype

Which classification are you assigned to? (1.0-4.5) TBA 3.0~3.5

(Stationary stage)What do you think of the seat width fitting level?
0 1 2 3 4 5 6 7 8 9 10 — perfect fit/ no discomfort … not fit/ max discomfort (marked: 5)

(Moving stage)What do you think of the seat width fitting level?
0 1 2 3 4 5 6 7 8 9 10 — perfect fit/ no discomfort … not fit/ max discomfort (marked: 5)

How acceptable was the process of adjusting the seat width?
0 1 2 3 4 5 6 7 8 9 10 — easy/ convenient … hard/ very inconvenient (marked: 3)

How safe do you feel during the adjustment process?
0 1 2 3 4 5 6 7 8 9 10 — safe/ nothing to worry … really worried/ not stable (marked: 2 circled; 8 crossed out)

Would you like to try different seat widths?
0 1 2 3 4 5 6 7 8 9 10 — Yes and frequent … not at all (marked: 8)

- What features or feelings about the adjustable seat width worked well for you? Being able to adjust even after transfer
- What problems did you notice, or what would you want changed? it lacks backrest options for this type of adjustability
- How does this seat width feel in comfort compared to your current chair? It can go smaller which is great
- In your opinion, what benefits could adjustable seat width bring? (personal / community) transfer accesibillity
- Other feedback? None

23/09/2025

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Research Survey
Test of basketball wheelchair seat width adjustment prototype

Which classification are you assigned to? (1.0-4.5) 1.0

(Stationary stage)What do you think of the seat width fitting level?
0 1 2 3 4 5 6 7 8 9 10 — perfect fit/ no discomfort … not fit/ max discomfort (marked: 2)

(Moving stage)What do you think of the seat width fitting level?
0 1 2 3 4 5 6 7 8 9 10 — perfect fit/ no discomfort … not fit/ max discomfort (marked: 1)

How acceptable was the process of adjusting the seat width?
0 1 2 3 4 5 6 7 8 9 10 — easy/ convenient … hard/ very inconvenient (marked: 4)

How safe do you feel during the adjustment process?
0 1 2 3 4 5 6 7 8 9 10 — safe/ nothing to worry … really worried/ not stable (marked: 1)

Would you like to try different seat widths?
0 1 2 3 4 5 6 7 8 9 10 — Yes and frequent … not at all (marked: 1)

straps.

- What features or feelings about the adjustable seat width worked well for you? the adjustability was quite handy
- What problems did you notice, or what would you want changed? the location of the crank — someone may not
- How does this seat width feel in comfort compared to your current chair? really comfortable — Adjust after getting in
- In your opinion, what benefits could adjustable seat width bring? (personal / community) It could make getting in easier
- Other feedback? N.V.T

23/09/2025

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Research Survey
Test of basketball wheelchair seat width adjustment prototype

Which classification are you assigned to? (1.0-4.5) 2.5

(Stationary stage)What do you think of the seat width fitting level?
0 1 2 3 4 5 6 7 8 9 10 — perfect fit/ no discomfort … not fit/ max discomfort (marked: 3; 7 scribbled out)

(Moving stage)What do you think of the seat width fitting level?
0 1 2 3 4 5 6 7 8 9 10 — perfect fit/ no discomfort … not fit/ max discomfort (marked: 4)

How acceptable was the process of adjusting the seat width?
0 1 2 3 4 5 6 7 8 9 10 — easy/ convenient … hard/ very inconvenient (marked: 4)

How safe do you feel during the adjustment process?
0 1 2 3 4 5 6 7 8 9 10 — safe/ nothing to worry … really worried/ not stable (marked: 1)

Would you like to try different seat widths?
0 1 2 3 4 5 6 7 8 9 10 — Yes and frequent … not at all (marked: 5)

- What features or feelings about the adjustable seat width worked well for you? Yes
- What problems did you notice, or what would you want changed? Handel at Front under the seat
- How does this seat width feel in comfort compared to your current chair? Fine — No side guard so differ.
- In your opinion, what benefits could adjustable seat width bring? (personal / community) Fine For New People to Train Speed in [illegible]
- Other feedback? good For universal Chair.

23/09/2025

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Appendix Q

Detailed price estimation

Although the specific production settings and requirements are not yet fully settled, a cost estimate for the additional seat width adjustment structure can still be made based on the envisioned production method. The overall cost is estimated from the unit cost based on the bottom-up method. The parts involved are as follows:

1. Handle bar (Injection molding)
2. Center Frame (Casting)
3. Connectors (CNC)
4. 4-bar mechanism connection rods (CNC)
5. Lead screws and nuts (Standard parts, out sourced)
6. Sideguard supports (CNC)

Handle bar	Based on a production of 1000	
Material cost	0.03 kg × $3.0/kg $	$0.09
Machine cost	$15 / h ÷ 120 per h	$0.125
Human labor cost	$0.05 + $0.02	$0.07
Mold cost	$8,000/1000	$8
Scrap and repair cost	30%	+30%
Total		$10.77

Lead screw and nuts	Out source	
Cost		$20

Center frame	Based on a production of 1000	
Material cost	300×2.7/1000 kg × $5.0/kg	$4.05
Process cost	$6 + $20	$26
Mold cost	$30,000/1000	$30
Scrap and repair cost	30%	+30%
Total		$78.07

CNC parts	Connection rods, supports and connectors	
Material cost	600×2.7/1000 kg × $5.0/kg	$8.1
Scrap cost	$8 × 30%	$2.4
Machine + Labor cost	$60 / h × 2 h	$120
Surface treatment cost	$6 × 8	$48
Mold cost	$1,200/1000	$1.2
Other indirect costs	25%	+25%
Total		$224.63

Assembly		
Assembly cost	$35 / h × 0.4 h	$14
Hardware cost		$5
Final cost		$353.5

Tax & Interests		
Tax	9%	$31.92
Manufacturer interests	30%	$106.05
Suggested price		$491.37

The weight involved is the larger value of the size in the model taking into account the loss, and the scrap loss and interest are also the larger values in the industry. Meanwhile, since the background wheelchair price is in US dollars, the cost estimations here are also calculated in US dollars.

The final estimated cost was $353.50, with an added selling price of $491.37.

Appendix Q

Detailed price estimation

Source of CNC

Aluminum 6061 cost per kg: Current Market Prices. (2025). https://www.accio.com/plp/aluminum-6061-cost-per-kg

Sugar Marketing. (2025). The True CNC machining costs per 1 hour in the UK - Ultimate Guide - Swift-Cut CNC Plasma Cutting Machines. https://swift-cut.com/cnc-machining-costs-per-hour-in-the-uk/

CNC machining cost breakdown for aluminum parts. (n.d.). Aluphant-Custom Aluminum Machining Part Manufacturer. https://aluphant.com/cnc-machining-cost-breakdown-for-aluminum-parts/

Source of Casting

Ctadmin. (2024). Die casting vs. sand Casting vs. permanent mold Casting: Cast Technologies. https://casttechnologies.net/die-casting-vs-sand-casting-vs-permanent-mold-casting/

Amelia. (2025). Understanding sand casting Costs: A complete guide for procurement and business managers. Sino Industries. https://sinoindustry.com/sand-casting-costs-guide/

Source of Injection Molding

Li, J. (2025). Complete introduction to injection molding costs. First Mold. https://firstmold.com/tips/injection-molding-costs/

Jaycon-Dev. (2025). Injection Moulding Price: A 2025 Guide for Engineers & Procurement - Jaycon | Product Design, PCB & Jaycon. https://www.jaycon.com/injection-moulding-price-a-2025-guide-for-engineers-procurement/

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Hengrui Zhao **Student number** 5,801,591

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Designing of a System to Increase Affordability of Recreational Basketball Wheelchair

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Physical activities are quite essential for wheelchair users, but they often fail to meet the public health guidelines for physical activity because of insufficient opportunities. As the most popular wheelchair sport, wheelchair basketball faces a significant barrier to participate due to the high cost and extensive customization required for specialized wheelchairs. The reason is that a wheelchair dedicated to basketball differs from a conventional wheelchair in many ways, such as mass, camber, customized height and other features that require a high degree of fit to the user.
Many potential players cannot afford the price of such wheelchairs, and clubs and organizations struggle to provide adequate wheelchair facilities and have long relied on funding to maintain them. Meanwhile, as a team sport that requires enough people to form a team, wheelchair basketball is relatively inclusive, allowing players with different levels of disability to participate recreationally, including able-bodied individuals. It's not realistic and affordable for all of them to have their own wheelchairs. In many cases they need to share wheelchairs at clubs or in the community, but body dimensions and use preferences vary greatly from person to person, so adaptability of the wheelchair is also important. Therefore cheaper and more adaptable yet still customized basketball wheelchairs could undoubtedly breathe a lot of life into the sport, attract more people to participate and enhance their well-being.

→ *space available for images / figures on next page*

introduction (continued): space for images

image / figure 1 A scenerio of playing recreation wheelchair basketball

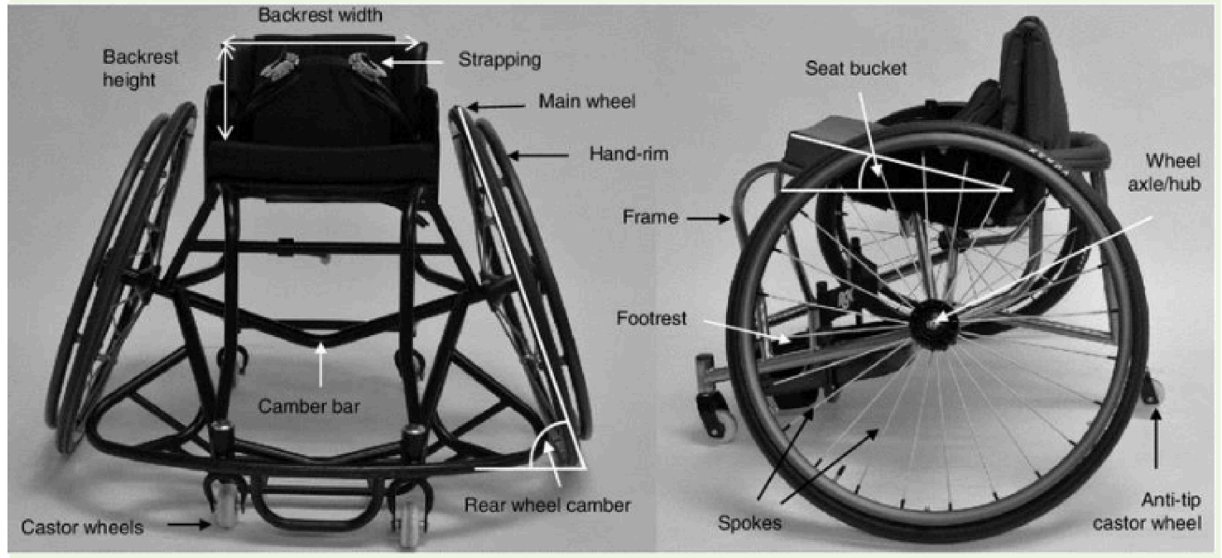

image / figure 2 A front-on and side-on view of a typical courts sports wheelchair demonstrating the major individual

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Current basketball wheelchairs are not affordable for many people in recreational context which limits accessibility and hinders the sport's growth. This project aims to make wheelchair basketball more inclusive by innovating in mechanical design and manufacturing, focusing on cost reduction while balancing the adaptability and customization of basketball wheelchair.
Ideally, the design will help get more people involved in and able to enjoy the sport of wheelchair basketball, also help organizations to get more active in the sport. By improving accessibility and participation, the development of wheelchair basketball empowers players with greater independence, confidence, and opportunities for teamwork, ultimately strengthening both individuals and the broader community.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design a basketball wheelchair to reduce costs while mainteining customization for players in recreational situations.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

The research should initially be based on the materials, manufacturing processes and functions, as well as customized adaptations of existing basketball wheelchairs, simultaneously integrate the development of other relevant adaptive devices. It will be also helpful to analyze the design approaches of other low-cost customized devices, and learn about advanced manufacture techniques. Combined with insights into stakeholders and user scenarios, I hope to build a comprehensive understanding of basketball wheelchairs and identify design opportunities to optimize the path to advanced affordability and customization.
Design by doing process will be conducted in parallel with the later stages of desktop and field research. Ideation methods will include, but not be limited to sketches, 3D rendering, varying levels of prototypes and tests to refine the design. My vision for the output is to integrate advanced manufacturing techniques, possibly 3D printing related, to control costs while mainteining necessary features and fitting level, as well as try to make the same product available to more people of different sizes and needs.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting, mid-term evaluation meeting, green light meeting*** *and* ***graduation ceremony****. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	20 Feb 2025
Mid-term evaluation	21 Apr 2025
Green light meeting	23 June 2025
Graduation ceremony	18 Aug 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

Primiraly, aspects of wheelchair design were introduced to me at the undergraduate thesis level and much reinforcement followed.
1.During my study in the Msc programme, I've participated in many Medisign relevant activities, courses and electives, from which the idea of designing for people with disabilities has been continually reinforced.
2.Sufficient skills and experiences of developing sizing system as well as knowledge of human anthropometry are also essential competencies for this project, and I acquired these in the Biomechanics elective.
3.My design experience in advance enbodiement design course contributes to this choice as well. It was about an accessible lavatory on the plane designing for people with limited mobility, which has further enhanced my experience and interest in designing for wheelchair users.
In the meantime, there are some personal learning ambitions that I've always wanted to explore and realize as a designer.
1.I have a lot of experience designing for wheelchair users, but it's almost always making up for their shame and hardship, this time I wanted to understand and design something they could enjoy.
2.I want to touch more on the realities of business and manufacture, thus design items ready for production and commercial practice.
3.Sports design is also my interest and I want to learn more about balancing safety, cost and performance.