Design Showcase 1 Report

University of Waterloo
Department of Systems Design Engineering

Design Team 15:
Rylin Soto - 20942344
Agam Soni - 20948293
Jamie Kang - 20956456
Livia Murray - 20928120
Joel Lee - 20948926

Date of Submission: October 29, 2021

Contents

Situation of Concern and Situation Impact Statement

Situation of Concern:

In the United States alone, about 3.6 million people use wheelchairs and 11.6 million people use other mobility assistive devices [1]. Of the non-wheelchair users, about 4 million people use canes and 1.5 million use walkers [2]. Those who are using mobility assistive devices are often older adults or those with clinical conditions that impact mobility like spinal cord injury, stroke, peripheral neuropathy, muscular dystrophy, multiple sclerosis, arthritis, and others [1,3]. These devices are typically used daily to assist with activities of daily living in indoor and outdoor environments [4]. Even though there is a large use of mobility assistive devices in society, these devices are not perfect. In fact, between 19 and 29% of prescribed devices are abandoned by their users [5,6]. This abandonment rate is relatively lower for wheelchairs (~10%) but higher for crutches and walkers (~30%) [6]. One thing these three devices have in common is that they can require two-handed use to achieve full mobility. This two-handed use can limit users in terms of the activities they can perform while also using the mobility assistive device for its intended, primary purpose: mobility. For example, carrying, identified as a secondary use case for mobility devices, could be challenging with a two-handed device [4]. Other, more complex instrumental activities of daily living like pet care, child rearing, housekeeping activities (e.g., landscaping, snow removal, repairs, meal preparation etc.) [7] could also be challenging to accomplish with a mobility assistive device that requires two-handed use.

There are some existing products that are designed to assist users with carrying tasks. One of the most popular walkers, Rollators or four-wheeled walkers, often have built in baskets to assist with carrying tasks [3] and range in price from $130 to $300 [8]. However, they provide less stability than other walkers and only assist with carrying items that are not a spill risk. Similarly, bag attachments are available for wheelchair type devices that range in price from less than $10 [9] to $20 [10]. To assist with carrying liquids (e.g., coffee cups), cup holder attachments are available for mobility assistive devices, like a $23 'universal' unit [11]. However, customer comments suggest that this device does not always achieve its 'universal' claim or have the needed stability [11]. Fewer devices are available for crutches, likely because these devices are more often used to address short term mobility issues. However, a few attachable bag solutions are available ranging in price from $15 to $20 [12,13]. These solutions are only suited to carrying items that are not a spill risk and have limited storage capacity. This demonstrates that when focusing on one of the identified tasks, the task of carrying, there is still a need for solutions that can support a wide range of carrying tasks that provide the needed storage capacity, universal attachment functionality, and stability to prevent spillage of or damage to carried items. It is likely that similar unmet needs still exist when examining the other activities of daily living.

This situation of concern is replicated in its entirety from [14]

Situation Impact Statement:

Therefore, there is a need to design an affordable modified wheelchair to be used by people afflicted with a disability constraining lower body control and movement to relieve them from using their upper extremities - thereby allowing them to complete other tasks and daily activities independently while simultaneously moving.

Requirements and Constraints

Requirements (in order of importance - based off QFD):

- Should be efficient
- Should be durable (crash test)
- Should have quick responses (break time)
- Should be affordable by comparison
- Should be user centric - product should be tailored to the user's abilities and [15] [16]
- Should be durable (weather test)
- Should be light (weight)
- Should be comfortable

Constraints:

- Must not exceed project deadline
    - Critical Value: No more than 10 weeks
- Must not exceed project budget
    - Critical Value: No more than $21,000 CAD [20]
- The dimensions of the wheelchair must not impede on the user's ability to access corridors, sidewalks and other pathways
    - Critical Value: Overall length: 1200mm / width: 700mm / height: 1090mm
- Must not inhibit reach, flexibility and dexterity of the upper torso by a substantial amount
    - Critical Value: The wheelchair shall not inhibit the user's upper torso by more than 5%

Ethics Based Requirement: (Requirement 6)

The ethics based requirement considered in the development of the wheelchair modification design is that the design product's metrics should be user-centric, more specifically that the product should be tailored to the user's abilities. This requirement is in alignment with *Public Guideline of the Code of Ethics* [15] (Engineering Canada) as well as the '*Ethical by Design' - Manifesto* [16], which yielded the general ethics idea that the wheelchair modification should cater to the needs of the users through engendering empathy for the users. This requirement reflects the products need to be accessible to a diverse demographic of users by creating either/both calibration based or customizable parts that can adapt to the user's specific level of disability. In conjunction with both safety and efficiency requirements, the ethics based requirement amplifies important values in the design which aim to create the most optimal user experience and solution to the design problems space.

Standard Based Constraints: (R6 & C3)

The standard-based requirement 6 and constraint 3 are measured using the *CSA Standard CAN/CSA-Z323.4.2-M86* [17], which lists methods for the determination of overall dimensions, mass, and minimum turning space for both manual and electric wheelchairs. Specifically, constraint 3 focuses on not impeding the user's ability to access public spaces. It is based on meeting the dimension regulations listed in clause 4.2 of standard [17]; meeting these regulations ensures that the user is able to access standard-sized corridors, hallways and sidewalks with the wheelchair. It is of importance that this constraint is met, as the inability to fit through spaces restricts mobility and accessibility of the wheelchair.

Personas

The primary persona developed is David, a 23-year-old former Canadian basketball player who played in the Spanish basketball league. During a late-night practice, David tore his ACL putting a halt on his basketball career. David became depressed and careless about his well-being, which resulted in him getting hit by a car ensuing in paralysis. Once again David suffered from intense depression due to giving up dream career and having to now navigate life in a wheelchair which came with a handful of other issues, like unwanted attention in public, little to no opportunities for jobs, and most prominently, finding it difficult to alternate between moving his chair and performing common tasks. Even his fiery passion for basketball had seemingly flickered out, as playing in a wheelchair just wasn't the same. His turning point was when he was contacted by Michael Jordan along with a sponsor; a company that produces affordable wheelchairs designed to liberate the user's hands from exclusively pushing the wheelchair. With his new wheelchair, playing basketball felt just that much more normal and natural for David and he is now more determined than ever, and is inspired to take back his health and life.

The secondary persona developed is a middle-aged woman named Janet, she and her husband and three sons live in Waterloo, Ontario. Up until three years ago, Janet worked her dream job as a marketing consultant but gave that up to be a full-time caregiver for her son, after he suffered a spinal cord injury due to a car accident resulting in paraplegia. Janet experiences many of the same psychological issues as other caregivers like her [18]. This includes anxiety and depression as she feels the need to always be near Matthew out of fear that he will get hurt but because of this, she cannot have time for herself. She thinks reentering the workforce part-time will allow her to feel like herself again. However, she feels she cannot because her son has a hard time maneuvering in his manual wheelchair in and outside the home and she often has to help by pushing the chair for him. Janet likes the idea of an electric wheelchair that will keep him active but the wheelchairs available on the market are either too expensive or her son doesn't like the style.

These personas enabled us to see both sides of the same coin, they helped us focus on making a design to both solve our situation of concern and be realistic. When researching and writing about our primary persona, David, we were able to narrow down our target audience for our solution. We decided that the user should want to maintain an active lifestyle in their wheelchair, much like David. With our secondary user, Janet, we considered what impact our solution could have for people not directly using the product, something we had not actively considered before. Her middle-class family would also be an exemplar of the average client which reinforced the idea that our product should stick to the side of simplicity in order to keep the cost down.

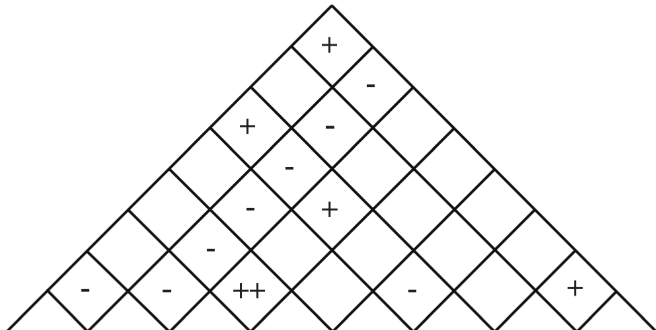
Quality Function Deployment (QFD) Chart

Overview:

Through this QFD it was realized that the requirement that the wheelchair modification should be efficient was the most important, while the comfortability defined on a basic level (such as the customizable back, arm, and footrests) yielded the least important ranking on a quantitative basis. The results from the QFD analysis are similar to that of the Pairwise Comparison Chart; the requirement "should be efficient" was given a score of 4 as seen in Tab. 5, making it the third most important requirement. Moreover, the "Should be comfortable" requirement got a score of 2 as seen in Tab. 5, making it one of the least important as others. The QFD analysis provided a more quantitative ranking of the requirements, whereas the Pairwise Comparison Chart gave rankings that were subjective, and opinion-based. The key change between the QFD analysis and the Pairwise Comparison Chart is that there were some other requirements that were found to be far more important in the QFD analysis than in comparison to their level of importance in the Pairwise Comparison Chart. For example, our ethnic requirements "Should be user-centric" and "Should be affordable by comparability". The changes in the level of importance for these requirements are due to the fact that from watching the stakeholder interviews[19] our group had noted that there was much more requirement for affordable wheelchairs since the majority of the existing wheelchairs in the market are expensive and unaffordable by some users. Also, our ethics requirement came out to be important in the QFD analysis and was not rated in the Pairwise Comparison Chart since the ethics requirement making design activity was in week 4 and not in the same week as the one in which we did the Pairwise Comparison Chart. Lastly, the significant changes in the QFD analysis and Pairwise Comparison Chart are due to the gained information and knowledge from the stakeholder interviews.

<u>QFD Chart:</u>

Table 1: Quality Function Deployment Chart



User Needs / Functions	Importance (What)	Should be efficient ↑	Should be affordable by comparability ↓	Should have quick responses (break time) ↓	Should be durable (crash test) ↑	Should be durable (weather test) ↑	Should be light (weight) ↓	Should be comfortable ↑	Should be user centric (tailored to the user's abilities) ↑		[20] Omeo ($22,500, 110kg, 12mph, mass 75kg)	[21] Karman LT-980 Ultra Lightweight wheelchair ($473, limited adjustments available, max mass 250lb, wheelchair weight 13lb)	[22] COMFYGO's Lightweight Electric Wheelchair ($1,500, max user weight 135kg, wheelchair weight 62lb)
Must be safe	18			9	9	3			1		4	3	3
Must be comfortable	10							9	1		4	3	3
Must be accessible	10		9						9		2	5	3
Should be affordable / save money	12		9				1				1	5	2
Improves mobility	14	9		3			9				5	2	4
Durable	10				9	3					4	2	3
Improves efficiency of tasks	18	9		1					3		4	3	3
Suitable for various weather conditions	8			1	1	9					3	1	2
Unit		%	$ (CAD)	seconds	Newtons	Likert (1-5)	kg	Likert (1-10)	Likert (1-5)				
Importance (HOW)		288	198	230	260	156	138	100	172	**1542**			
Importance (%)		18.7	12.8	14.9	16.9	10.1	8.9	6.5	11.2				
Minimum Threshold		40	8,000	1.5	1500	1	50	1	1				
Desired Target		60	12,000	2	2400	4	90	8	4				
Maximum Threshold		100	22,000	3	3300	5	113	10	5				

(Column groups: Engineering Requirements — first nine columns after Importance; Competitive Products — last three columns.)

<u>Relationship Matrix:</u>

The Relationship Matrix is used as a means of evaluating the interdependencies between the user's needs and the engineering requirements with a 1 indicating slight interdependence (S.I), 3 being moderate interdependence (M.I), and 9 representing high interdependence (H.I).

- Must be safe:
  - H.I with a shorter break time as it ensures the user can stop or slow down to avoid collisions or potential hazards.

    - H.I with durability (crash test) as a better ability to withstand a collision will reduce the severity of injuries on the user in the event of a collision.
    - M.I with weather durability because it protects the user from weather conditions
    - S.I with user centrism as it allows for the user to find and maintain optimal control of the wheelchair.
- Must be comfortable:
    - H.I with comfortability as having a more comfortable wheelchair will lead to a more comfortable experience for each user.
    - S.I with user-centricity as having the wheelchair customized according to the user often leads to a more comfortable experience.
- Must be accessible:
    - H.I with affordable by comparison as an affordable wheelchair opens up the consumer base to more people across different economic classes.
    - H.I with the wheelchair being user-centric. This is because the wheelchair is not exclusive to a certain height, weight, or size of an individual in order to be used, thereby increasing how many people can use the wheelchair.
- Should be affordable/save money
    - H.I with affordable by comparison as an affordable wheelchair will enable the user to save money and also view the wheelchair to be affordable when compared to competitors.
    - S.I with the weight of the wheelchair as material like plastic is cheap and light while alloys and metals are generally more expensive and heavy.
- Improves mobility
    - H.I with efficiency, as it decreases the input (time and energy) required to complete said task.
    - H.I with the wheelchair being lighter as it enables faster acceleration and deceleration which can be helpful when turning corners or making a sudden stop.
    - M.I with quick responses/break time as it improves the wheelchair's ability to stop and change direction.
- Durable
    - H.I with durability in a crash test as withstanding more pressure and force demonstrates high durability.
    - M.I with durability in weather conditions because weather can be specific to the user and their geographical location.
- Improves efficiency of tasks
    - H.I with the efficiency of the wheelchair as it reduces energy consumption and time, thereby improving the efficiency of tasks.
    - M.I with user centrism - tailored to user ability. Customized sensor sensitivity according to the user enables better control of the wheelchair's movement, increasing efficiency.
    - S.I with quick response time/break time since tasks like cooking and cleaning often require sudden changes in directions.
- Suitable for various weather conditions
    - H.I with durability in various weather conditions as resistance/adaptations to extreme temperatures and environmental variables (Hail, snow, rain) improves suitability.
    - S.I with quick responses/break time as it can often help to prevent collisions during the winter when there is a lack of traction due to ice or snow.
    - S.I with being durable in a crash test as high durability is suitable for potential crashes or collisions during the winter season.

<u>Correlational Matrix:</u>

The correlation matrix serves to demonstrate the interdependencies between engineering designs requirements:
-Various pluses and minuses represent the degree of interdependence: a "- -" representing a strong negative correlation (S.N.C), "-" negative correlation (N.C), "+" positive correlation (P.C), and " + +" strong positive correlation (S.P.C). Blank interdependencies represent no relationship or a neutral relation between engineering relationships.

- Should be efficient
  - N.C with "should be affordable by comparison": features affecting efficiency would increase the cost
  - P.C with "should be light (weight)": decreased weight would allow for increased speed and therefore the efficiency of completing tasks.
  - P.C with "should be user-centric": user-centricity in completing tasks is directly related to the efficiency of which the user is enabled by the device to complete the task at
- Should be affordable by comparison
  - N.C with "should be efficient, should have a quick response time (break time), should be durable (crash test), should be durable (weather test), should be light (weight), should be comfortable, should be user-centric" because all requirements would increase the cost by adding independent features
- Should have a quick response time (break time)
  - S.P.C with "should be durable (crash test)": a quick response time would better avoid impact
  - P.C with "should be user-centric": safety is an imperative user expectation and function
  - N.C with "should be affordable by comparison": increased safety equipment would also increase the price drastically
  - P.C with "should be light" because a lighter chair would have a quicker response time because it requires less force to stop
- Should be durable (crash test)
  - S.P.C with "should have a quick response time": a quick response time would better avoid impact and survive the crash test
  - N.C with "should be affordable by comparison": increased safety equipment would increase the cost by adding features
- Should be durable (weather test)
  - N.C with "should be light": to be adaptable to different geographics and weather concerns, more specific equipment would be added which would result in a weight increase
  - N.C with "should be affordable by comparison": cost would increase by adding features that would better suit the wheelchair for diverse weather conditions
- Should be light (weight)
  - P.C with "should be efficient": efficiently and speed with be directly impacted by decreasing weight
  - N.C with "should be affordable by comparison": lighter weight metals for constructing the wheelchair would increase the price of the wheelchair
  - P.C with "should have a quick response time": lighter weight materials would require less energy to stop the designed wheelchair
  - N.C with "should be durable (weather test)": more weather equipment would cause the wheelchair to be heavier
- Should be comfortable
  - P.C with "should be user-centric": customizable parts may increase the user's ability to effectively control the movement mechanics of the wheelchair
  - N.C with "should be affordable by comparison": customizable parts would increase the cost

- Should be user-centric
    - P.C with ‘should increase efficiency”: users require the efficiency to increase in order to perform the task without the use of their arms
    - N.C with “should be affordable by comparison”: more user-centric characteristics that include some means of customization would directly increase the price
    - P.C with “should be comfortable”: user centrism would increase with comfortability and the user’s ability to more effectively control the wheelchair

Functions and Means

The ultimate goal of the modified wheelchair solution is to relieve the user of the need to use their upper extremities (hands/arms) to control movement - thereby allowing them to complete other tasks and daily activities they were unable to efficiently complete independently while simultaneously moving.

The first basic function that our modified wheelchair must possess is the ability to aid in the mobility of the user. In other words, the wheelchair must move and stop upon the user's request. The importance of this function can not be understated, as this modified wheelchair will ideally give the user a sense of freedom otherwise not attainable by current manual or generic electric wheelchairs on the market. This sense of freedom will not be attained if the wheelchair does not function properly upon the user’s intended commands. This function also coincides with our requirement as seen in Tab. 3, which states, “The modified wheelchair should be efficient.” In order to fulfill this need, the wheelchair must be able to move forwards, backward, right, and left, in addition to stopping and remaining stationary, all without the need for the user to freely move their upper extremities. Without this function, the wheelchair would not fulfill our situation impact statement and would not be a viable problem space solution.

Since the modified wheelchair must be electric, there is a need for the wheelchair to obtain power, store it and use it. It is important that the method is fast and long-lasting so that the user would not have to plan their day around the charging of their wheelchair. The power of the wheelchair directly affects its overall functionality and the user’s satisfaction. These are correlated to the efficiency requirement as previously mentioned as well as the requirement (seen in Tab. 3) that states our solution, “must cater to the needs of the users by engendering empathy for the users.” It must be taken into consideration that individual user’s circumstances and routines may vary greatly, and that the design should efficiently fit all users' needs to the best of our abilities.

It would be fair to assume that similar to all other electrical-powered products, our modified wheelchair may be susceptible to overheating. In more severe cases this disturbance may result in a system malfunction or an electrical fire. Therefore, we have established there is a need for a cooling system. Wheelchair electrical fires are not necessarily common but it is important to take safety measures into consideration as when they do, they are extremely destructive [23]. This links to our requirement, in Tab. 3, that the wheelchair “must be safe.” Thus, it is our responsibility to ensure that no such accident happens by ensuring this function be honorably upheld in our design.

The fourth basic function is that our modified wheelchair must support user tasks. Two secondary functions fall under this notion. The first is that the wheelchair will be fully controlled by the user and secondly, the wheelchair shall not impede the upper extremity freedom of the user. The importance of these functions are directly related to the situation impact statement, which addresses the need for a solution that allows for an increased freedom in the user’s experience. User’s must be able to have full, independent control of the device and the device itself will not impede their newly developed freedom or safety concerns in order to satisfy the function of supporting user tasks.

Since the modified wheelchair would be used in a variety of geographical locations, our solution will need to resist most weather conditions that our users might be encountering and adapt the wheelchair accordingly. These needs are in line with our requirement in Tab. 3, that states our design, "Should function equally well in all weather conditions." For the well-being of our client, it is critical that our mechanics do not freeze when the temperature is too cold, and conversely, our design must not melt when the weather is too hot. It is equally important that our design is able to withstand rain, as we would aim that the modified wheelchair be suitable in both indoor and outdoor environments.

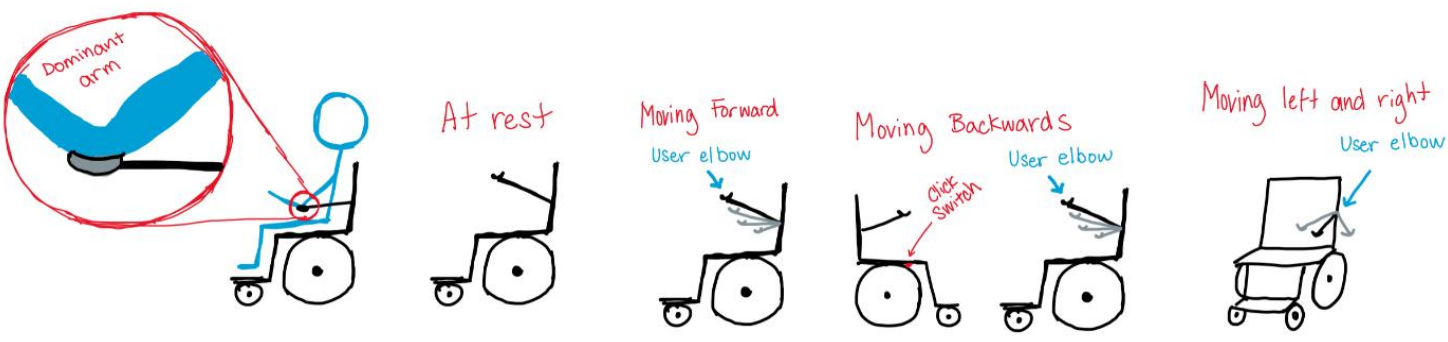
Our sixth and final identified function is that the chair will be comfortable for the user. Having a functioning wheelchair that allows the user to control it without their hands is worthless if it is not comfortable for the user. Unfortunately, an issue that affects the majority of wheelchair users is pressure sores, and one of the best ways to attack that statistic is with proper cushioning [24]. It's importance is also demonstrated as a requirement, Tab. 3, that states "For each individual patient, the back, arm, and footrests in addition to the seat dimensions should be customizable." Since wheelchairs are not one size fits all, the design must be customizable to each individual wheelchair user, ensuring maximum comfort for a diverse user population.

Design Concepts

When taking into consideration the needs and requirements, the wheelchair must be efficient, safe, lightweight, durable, comfortable, and cater to users' needs. Overall, the cost of the wheelchair must be affordable in comparison to other wheelchairs in the market for it to be accessible to the general user group population. These requirements are created to address the growing issue of wheelchair users abandoning their mobility device since the "two-handed use...limit users in terms of the activities they can perform while also using the mobility assistive device for its intended, primary purpose: mobility." [14] Therefore, the synthesis of wheelchair modifications must allow the user full availability of their upper extremities to do other tasks while the mobile device moves them in their desired direction. The design concepts which were created in the design generation activity largely follow the QFD requirements based on the percentage of importance. Each design concept has an order of consideration as follows: efficiency, cost, response timing, durability, weight, comfortability, and user-centricity which was taken into consideration when designing each design concept.

Retractable arm - elbow control:

Figure 1: Retractable arm sketch



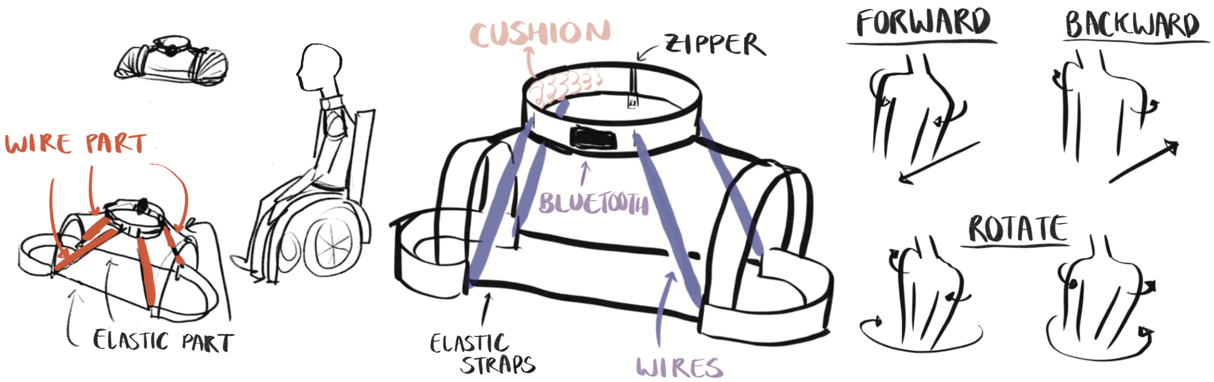
The key concept of the retractable arm is that the user's non-dominant hand in addition to their entire dominant arm is free while the chair is moving. The wheelchair will be similar to a general electric wheelchair with a retractable arm on the non-dominant hand side of the user. The position of the retractable arm will control the movement of the chair through the front wheels. To move forward the user must press down on the arm until it clicks, then, the farther they press down the faster they will go. The backward movement will function the same only the user must first click a switch on the dominant hand side of the chair, and unclick when they wish to move forwards again. To move left or right the user must turn the retractable arm in the respective direction and exceed some dead zone limit to initiate movement.

A possible advantage of this design alternative would be that the mechanics of this design are not very different from the average toggle-controlled electric wheelchair, therefore this design follows the requirement to be affordable by comparison. Additionally, the wheelchair will be able to function at a lower weight since the elbow connection togel mechanics are not very complex. This also caters to the requirement that it should be efficient, with fewer mechanics the machine will take less time to charge, and having it lightweight conserves the battery power for a longer period of time.

In addition to these advantages, the retractable arm also presents certain disadvantages and challenges with the design. Firstly, the user's arm may get tired after long periods of use, and exertion of the patient's non-dominant arm being a key factor pertaining to continual movement may decrease its functionality on a day-to-day basis. This may present concerns towards poor blood circulation in their non-dominant arm with it being in a constant elevated position. In terms of durability in extreme cases, the retractable arm may be subject to breaking off as an extendable part. Otherwise having a large arm protruding from the wheelchair may be dangerous for surrounding people and children when not in use. Finally, this design concept does not fully adhere to our team's design impact statement as it still requires the use and restriction of one arm to be controlled.

<u>Shoulder Bluetooth control:</u>

Figure 2: Shoulder Bluetooth control sketch



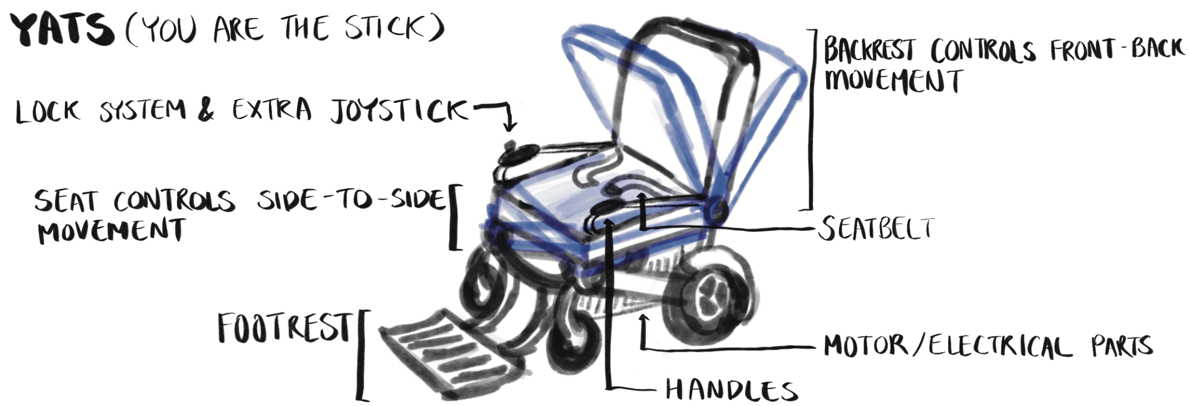
The focal point of this design is the replacement of the joystick/controller of a conventional motorized wheelchair with a Bluetooth-connected movement tracking device worn on the user's shoulders. The four wires connecting the shoulder straps to the main device around the neck record the movement of the shoulders by measuring the displacement of the wire length from the default position/length. Scrunching the shoulders forward will tell the wheelchair to go forwards; leaning the shoulders back will tell it to go backward. By pointing the shoulders in the wanted direction, the device will cause the wheelchair to rotate as well. The main device around the neck will be constantly calculating the movement of the shoulders and send back instructions to move the wheelchair accordingly through Bluetooth. The lining of the main device against the skin of the neck is well cushioned to avoid scuffing, while the two shoulder straps are connected to each other with an elastic strap placed across the chest to keep the device secure on the shoulders.

This device frees both arms from having to control the wheelchair, as well as the back of the user (due to Bluetooth connection) which adheres well to our situation of concern statement. The design would be made to be worn inside clothing garments in colder weather; highly increasing the accessibility of the device in colder environments. It is also lightweight; using this control device will barely add weight to a standard weight motorized wheelchair. The device is highly reactive, which means it will give users some of their sense of control over their body back (the device simulates body parts) by utilizing ‘normal’ body movement mechanics.

Possible drawbacks of this design relate to the price and comfort of the shoulder apparatus. The technology needed to fit a device that can calculate shoulder movement around the user’s neck, as well as the Bluetooth components significantly, raise the budget needed. Moreover, no matter how compact the device is, having a device that wraps around the neck for an extended amount of time can be very uncomfortable especially in hot and humid environments and may present possible concerns as to pressure sores after elongated periods of use. Another concern to the usability of this device is the case when the user makes complicated movements with their upper torso that include the shoulders; without shoulder movement, the range of movement possible while using this design will be limited.

YATS - Back control:

Figure 3: YATS sketch



The YATS design alternative involves integrating a pressure sensor in the seat as well as a gyroscope on the backrest that measures its angular position in order to determine the desired movement of the user. It utilizes the back rest’s angular position to determine which direction the user wishes to move in. For example, leaning forwards will move the wheelchair in the forward direction while leaning backward causes the wheelchair to move backward. The pressure sensors are used to detect any notable leaning that the user does exceeding some calibrated limit, responding by rotating and turning the wheelchair accordingly. Leaning to the left and right will turn the chair in the same direction with the steepness of the turn being dependent on how much pressure is exerted by leaning. Moreover, thresholds are applied to each of the sensors to ensure that minimal movement does not lead to any unwanted movement, as such there exists a dead space in which the user’s movement does not affect the movement of the chair. These thresholds (sensitivity of the sensors) can be increased or decreased according to the user and their range of motion through an initial calibration session. The YATS also has a toggle switch that will disable movement in the chair in the event that the user wants to stop all movement, this could include stretching to reach something or even sleeping in your chair.

The advantage of the YATS is that it enables the user to fully utilize their upper extremities while moving, directly addressing many of the requirements in the situation of concern. As such, tasks like vacuuming, cooking, transporting, or even playing sports become that much easier and natural for the user. The wheelchair is also efficient because the chair directly responds to the movement of the user and hence no unnecessary movements are made.

A disadvantage of the YATS might be that its accessibility is mainly focused on individuals who have capable core strength and might otherwise be difficult for individuals who have an extremely limited range of motion in their torso. Another disadvantage is that it is heavier compared to other designs as it utilizes multiple sensors and motors to control the movement of the chair.

Concept Selection

Decision-making process:
Included a Google Forms voting process to select the 'top three' designs from the gallery method design concept generation phase. Then implemented Best of Class Chart to subjectively rank those designs on your engineering requirements in comparison with each other which allows for a qualitative evaluation and judgment based on metrics.

Vote Results:

- TOP 3: Retractable Arm, Shoulder Control, YATS (unanimously decided on prior to voting)

Figure 4: Top 3 designs voting result (choosing remaining two designs)

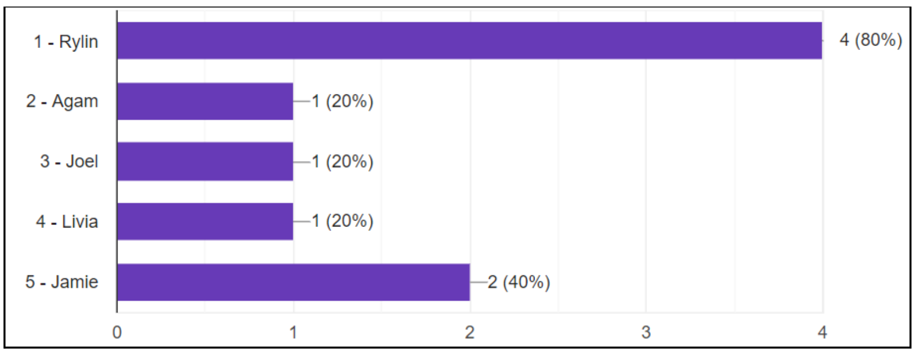


Table 2: Best of Class Chart - Comparison between three chosen designs:

Requirement:	**Design Alternative 1 (#1) Non-dominant elbow control (Retractable Arm)**	**Design Alternative 2 (#5) Shoulder control**	**Design Alternative 3 (#6) Back control (YATS)**
Should be efficient	3	2	1
Should be affordable by comparison	1	2.5	2.5
Should have quick response time (break time)	3	1	2
Should be durable (crash test)	2.5	2.5	1
Should be durable (weather test)	2	3	1
Should be light (weight)	2	1	3
Should be comfortable	2	3	1
Should be user-centric	3	2	1

The best of class chart provided a rough outline for team conversation concerning the design concept selection for our problem space. However it is important to understand that bias still exists in the BofC chart, and design options must be evaluated holistically and with the intention to represent user needs/wants and engineering requirements. While a best of class chart does allow for a qualitative evaluation and judgment of requirements, the results of the chart are not comparable to the actual discrepancies between factors, because of the scaling of the chart. An indifferent audience would not know the extent of how much better one design alternative is performing. It is not appropriate to sum those rankings across requirements and there must be a literal interpretation of to what degree the chart's results may be valued in the overall concept selection process. This is why a more comprehensive method was taken up when evaluating our design alternatives for concept selection.

The QFD posed several quantitative results, which were taken into consideration in the selection of the design. It was determined that 'should be efficient,' 'should be user centric' and 'should be durable' and safe (crash testing) evaluated to be the most important in relationship with customer needs and functions. These metrics were also highlighted in various user need evaluations throughout the needs assessment phase in the iterative design process; in the primary person development, stakeholder interviews, and our team's interview meeting with a primary persona type user, Braden. Each of these assessments of needs activities reinforced the acceptance of functions required in the wheelchair design modification to solve the problem of two-handed use being required to achieve full mobility and that factors impediment on the users' ability to complete some task. Through the iterative design process and in the team's design concept selection, it was exceeding apparent that design alternative #3 was the most optimal design to integrate into daily life in respect to the problem space. The YATS solution would essentially provide an intuitive, body-movement-based motion solution; meaning that little to no technical knowledge would be required in order to operate the wheelchair, which increases user accessibility. Another factor of the design that interplays with the user-centric nature of the YATS wheelchair is its initial calibration/customization process. For example, when you are setting up the device, there would be controls to set neutral positioning of the backrest and static movement, as well as boundaries for the backrest's dead zone for movement. The machine would then automatically scale the wheelchair's movement abilities according to the boundaries set by the user. These boundaries could then be adjusted throughout the user's lifetime, eliminating the need for multiple chairs and expensive machinery upgrades. The feature which most stands out as suiting the design problem space best is YATS adherence to the design constraint 'must not inhibit reach, flexibility, and dexterity of the upper torso by a substantial amount.' In both the elbow and shoulder connection design alternatives, there remains the factor that some piece of machinery or attachment would require to be connected to the user's upper extremities. This would decrease the convenience of the device as something it may be more difficult to implement into daily activities and lifestyles.

After the creation of the design, it was discovered that YATS would have direct competitors - Omeo, the Karman LT-980 Ultra Lightweight Wheelchair, and the Comfygo Motorized Lightweight Electric Wheelchair (as identified in QFD) - who shares similar mechanical patterns to the YATS solution, however, is on the market at $21,000. It was identified what features were excellent within the design of competitor products and then it became a goal that the same level of functionality would be achieved at a lower cost to the user using new innovative solutions. Moreover, each of the competitor products was given a rating out from 1-5 for its performance and fulfillingness for each of the user needs and functions based on the user ratings of the products [20][21] and reviews [22]. Some key user needs remain unfulfilled by the competitor products allowing us to incorporate solutions for them into our wheelchair so it is preferable on the market. In accordance with the engineering requirement and user function that the product be affordable by comparison the competitor's existence is evidence that the YATS solution would be successful on the same market as a less costly solution with similar functionalities with the calibration option to better appeal to user centrism.

Reference List

[1] J. Carver, A. Ganus, J.M. Ivey, T. Plummer, and A. Eubank, "The impact of mobility assistive technology devices on participation for individuals with disabilities," *Disability and Rehabilitation: Assistive Technologies*, vol. 11, no. 6, pp. 468-477.

[2] H. Bateni, and B.E. Maki, "Assistive devices for balance and mobility: benefits, demands, and adverse consequences," *Arch Phys Med Rehabil*, vol. 86, pp. 134-145, 2005.

[3] M.M. Martin, C.P. Santos, A. Frizera-Neto, and R. Ceres, "Assistive mobility devices focusing on Smart Walkers: classification and review", *Robotics and Autonomous Systems*, vol. 60, pp. 548-562, 2012.

[4] E. Hedberg-Kristensson, S.D. Ivanoff, and S. Iwarsson, "Experiences among older persons using mobility devices," *Disability and Rehabilitation: Assistive Technologies*, vol. 2, no. 1, pp. 15-22, 2007.

[5] B. Phillips, and H. Zhao, "Predictors of assistive technology abandonment," *Assistive Technology*, vol. 5, no. 1, pp. 36-45, 1993.

[6] A.T. Sugawara, V.D. Ramos, F.M. Alfieri, and L.R. Battistella, "Abandonment of assistive products: assessing abandonment levels and factors that impact on it," *Disability and Rehabilitation: Assistive Technologies*, vol. 13, no. 7, pp. 716-723.

[7] E. Orellano, W.I. Colon, and M. Arbesman, "Effects of occupation- and activity-based interventions on instrumental activities of daily living performance among community-dwelling older adults: a systematic review," *American Journal of Occupational Therapy*, vol. 66, no. 3, pp. 292-300, 2012

[8] "Rollators," *Global Industrial*, 2021. [Online]. Available: https://www.globalindustrial.ca/g/medical-lab/wheelchairs-1/medical-walkers-rollators/Rollators [Accessed 3 June 2021].

[9] "Wheelchair Side Hanging Bag Armrest Pouch Organizer Pocket Holder Reflective," *Wish*. [Online]. Available: https://www.wish.com/product/5df09de5d4ba3303a0ec9894?share=web [Accessed 3 June 2021].

[10] "Unisex Walker/Wheelchair Bags/Bedside Rail Pouch," *Silverts*, 2021. [Online]. Available: https://www.silverts.com/ca/unisex-walker-wheelchair-bags-bedside-rail-pouch [Accessed 3 June 2021].

[11] "Drive Medical Black Universal Cup Holder 3-inch Wide," *Walmart*. [Online]. Available: https://www.walmart.ca/search?q=Drive%20Medical%20Black%20Universal%20Cup%20Holder%20 3-inch%20Wide [Accessed 3 June 2021].

[12] "SupreGear Crutch Bag, Water Resistant High Quality Crutch Organizer Pouch Tote Crutch Accessories, Lightweight and Machine Washable (Black)," *Amazon*. [Online].

Available:https://www.amazon.ca/SupreGear-Resistant-Organizer-Accessories-Lightweight/dp/B07Q5WZFSB/ [Accessed 3 June 2021].

[13] "EZ-ACCESS Universal Crutch Carry On," *Arthritis Supplies*, 2021. [Online]. Available: https://www.arthritissupplies.com/universal-crutch-carry-on.html [Accessed 3 June 2021].

[14] J. Howcroft, "BME161 - Fall 2021 - Situation of Concern," September 2021. [Online]. Available :https://learn.uwaterloo.ca/d2l/le/content/709103/viewContent/3958790/View [Accessed September 2020].

[15] Engineers Canada: Public Guideline on the Code of Ethics, "The Code of Ethics," 29 March, 2016. [Online]. Available: https://engineerscanada.ca/publications/public-guideline-on-the-code-of-ethics#-the-code-of-ethics [Accessed 22 September 2021].

[16] Mulvenna, M.D., Boger, J., Bond, R.B., "Ethical by Design - A Manifesto," In *Proceeding of European Conference on Cognitive Ergonomics* 2017 (ECCE 2017), Umeå, Sweden, September 2017.

[17] National Standard of Canada, "Wheelchairs - Determination of Overall Dimensions, Mass, Turning Space.", CAN/CSA-Z323.4.2-M86, December 1986.

[18] Rushton PW, Labbé D, Demers L, Miller WC, Mortenson WB and Kirby RL, "Understanding the Burden Experienced by Caregivers of Older Adults Who Use a Powered Wheelchair: A Cross-Sectional Study," National Library of Medicine, Maryland, USA, 10, April, 2017 [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5406150/ [Assessed September 29 2021].

[19] J. Howcroft. BME161. Class Lecture, Stakeholder Interviews: "Connection Library - Jeremy - Wheelchair User - BME Cut." Biomedical Engineering, University of Waterloo, Waterloo, Canada, Sept, 26 2021. Available: https://learn.uwaterloo.ca/d2l/le/content/709103/viewContent/3983869/View [Assessed September 29 2021]

[20] K. Halsall, "Omeo Technical Specifications," *Omeo Technology*, February 10 2021. [Online]. Available: https://omeotechnology.com/omeo-technical-specifications/ [Accessed October 15 2021].

[21] Karman, "LT-980 ultra lightweight wheelchair" Karman Excellence Through Mobility, October 5 2021. [Online]. Available: https://www.karmanhealthcare.com/product/lt-980-ultra-lightweight-wheelchair/ [Accessed October 15 2021].

[22] "Fold & Travel motorized Lightweight Electric Wheelchair," Amazon, October 5 2021. [Online]. Available: https://www.amazon.ca/Motorized-Lightweight-Electric-Wheelchair-Aviation/dp/B08NFFMRKG/ref=sr_1_1?dchild=1&keywords=COMFYGO&qid=1634149019&sr=8-1&th=1/ [Accessed October 15 2021].

[23] Parker and Waichman LLP, " Wheelchair Fires Side Effects May Result In Wrongful Death Lawsuits," *Parker and Waichman LLP,* 2021. [Online]. Available: https://www.yourlawyer.com/defective-medical-devices/wheelchair-fires/ [Accessed October

27, 2021].

[24] Familydoctor.org, “Pressure Sores,” *Familydoctor.org,* November 2020. [Online]. Available: https://familydoctor.org/condition/pressure-sores/ [Accessed October 28, 2021].

[25] K.Nunez, (2018, August) “Does Your Jogging Speed Feel Right?” Healthline. [Online]. Available: https://www.healthline.com/health/average-jogging-speed [Accessed September 26 2021].

[26] Etac, “Wheelchair testing information,” Convaid, 18-Jan-2011. [Online]. Available: https://www.convaid.com/wheelchair-testing-information/ [Accessed: 02-Oct-2021].

[27] Anonymous Contributors, “How Do Hoverboards Balance?,” Swagtron, November 8, 2018. [Online]. Available: https://swagtron.com/faq/hoverboards/how-do-hoverboards-balance/ [Accessed September 29, 2021].

[28] Unnamed Contributors, “How to Use a Wheelchair,” WikiHow, March 20, 2021. [Online]. Available: https://www.wikihow.com/Use-a-Wheelchair [Accessed September 29, 2021].

[29] Susan Shore, Stephanie Juillerat B, “The impact of a low cost wheelchair on the quality of life of the disabled in the developing world,” NCBI (US National Library of Medicine National Institutes of Health), September 1, 2012. [Online] Available: https://www.ncbi.nlm .nih.gov/pmc/articles/PMC3560642/ [Accessed September 29, 2021].

[30] Louis Bruton, “23 Things That People In Wheelchairs Have To Cope With,” Buzzfeed, New York, USA, 17, September, 2015. [Online]. Available: https://www.buzzfeed.com/ louisebruton/everyday-struggles-for-a-wheelchair-user-f5b5 [Assessed September 29 2021].

[31] DeAnn R, Michael Morale, Kevin Schaefer, Ryan Berhar, “How Often Do You Replace Your Wheelchair?” SMA News Today, September 15-17 2018. [Online]. Available: https://smanews today.com/forums/forums/topic/how-often-do-you-replace-your-wheelchair/ [Accessed September 29, 2021].

[32] Ferry Vermeulen, “13 Crazy Tips to Create Magic IKEA-ish Manuals (Insider Secrets),” Instrktiv - User Instructions, February 15, 2019. [Online] Available: https://instrktiv.com/en/ikea-manual/ [Accessed September 29, 2021].

[33] Ashley Watters, Abshier House, Abshier House, “How to Ride a HoverBoard,” Dummies. [Online] Available: https://www.dummies.com/consumer-electronics/how-to-ride-a-hoverboard/ [Accessed September 29, 2021].

[34] Brian Chun-Fai Chan, Suzanne M. Cadarette, Walter P. Wodchis, Murray D. Krahn and Nicole Mittmann, “The lifetime cost of spinal cord injury in Ontario, Canada: A population-based study from the perspective of the public health care payer,” Taylor and Francis Online, 20, June, 2018. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/ 10790268.2018.1486622 [Assessed September 29 2021].

[35] Hongwu Wang , Hsin-Yi Liu, Jon Pearlman, Rosemarie Cooper, Alexandra Jefferds, Sam Connor and Rory A Cooper, “Relationship between wheelchair durability and wheelchair type and years of test,” National Library of Medicine, Maryland, USA, 2010. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/20131972/ [Assessed September 29 2021].

[36] Noh JW, Kwon YD, Park J, Oh IH and Kim J, “Relationship between Physical Disability and Depression by Gender: A Panel Regression Model,” National Library of Medicine, Maryland, USA, 20 November 2016. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5130183/ [Assessed September 29 2021].

Appendix

Requirements Table:

Table 3: Requirements table

	Description	*Measured Parameter*	*Testing or Evaluation Protocol*	*Metric*
R1	Should be efficient	Time (in minutes) to complete task	Ask patients to complete a chosen task in their current wheelchair and compare with the time taken with our solution	Goal is to decrease the patient's time needed to perform their chosen task by 60% or more.
R2	Should be affordable by comparison	Canadian dollars (CAD)	Compare our final costs to our competitors in terms of patient consulting/inquiring and product cost.	Keep costs to about 75% of the price of our competitors' [20] (about $10,000 - $15,000 compared to $21,000)
R3	Should have quick responses (break time)	Time (in seconds) of the response time	Measure the response time of braking with people of different weights.	Have response time be no more than 2 seconds at top speed ([25] 8km/h based on average jogging speed)
R4	Should be durable (crash test)	Force (Newtons)	Crash test – run a wheelchair down a ramp of various heights into a wall which will test the force at which the wheelchair hits it.	Final product should be able to withstand 2414N of force approximately equal to 30pmh/20g [26]
R5	Should be durable (weather test)	Lickert scale from primary user	Ask users from different environments to fill out survey: Rate on a scale of 1-5: 1 – strongly disagree 5 – strongly agree Q1. I have not noticed any changes in functionality in hot and cold conditions Q2. I have not noticed any changes in dry and wet conditions Q3. I feel confident that my wheelchair will not break down due to weather conditions	Goal is to receive results of 4 and above
R6	Should be light (weight)	Mass (kg)	Weigh final product	Final product should be between 50kg and 113kg (depending on size of the wheelchair) to allow some portability
R7	Should be comfortable	Lickert scale from primary user	After using our solution for 2-3 weeks, ask user to fill out survey: Rate on a scale of 1-10: 1 – not comfortable at all 10 – extremely comfortable Q1. Comfortability of seat cushion Q2. Comfortability of head rest Q3. Comfortability of foot rest Q4. Comfortability of back rest Q5. Overall comfort	Goal is to receive results of 8 and above
R8	Should be user centric – product should be tailored to the user's abilities and [15] [16]	Lickert scale from primary user	Ask user to fill out survey: Rate on a scale of 1-5: 1 – not well at all 5 – exceptionally well Q. Rate how well you feel that our solution has addressed your personal needs, wants, hopes and desires	Goal is to receive results of 4 and above

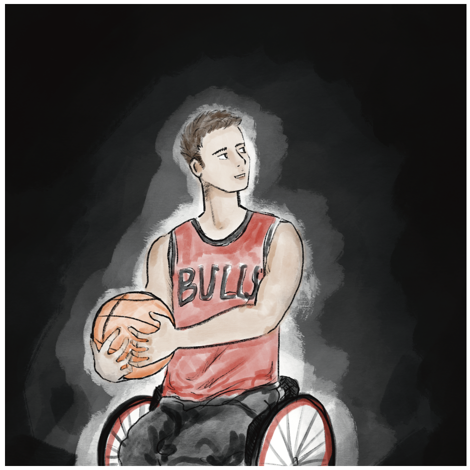
Constraints Table:

Table 4: Constraints table

	Description	*Measured Parameter*	*Testing or Evaluation Protocol*	*Critical Value*
C1	Must not exceed project deadline	Time (in weeks)	Tracking time spends on various design sprints	No more than 10 weeks: Course deadline and design presentations due: November 29 – December 7
C2	Must not exceed project budget	Canadian dollars (CAD)	Track costs of parts within a spreadsheet – calculate cost revenue margins	No more than $21,000
C3	The dimensions of the wheelchair must not impede on the user's ability to access corridors, sidewalks and other pathways	Millimetres (mm)	Adhering to the standard size limit of wheelchairs from [17]	Clause 4.2 from [17] "A wheelchair shall not exceed the maxima listed for the following dimensions: Overall length including leg support(s) and footrest(s): 1200mm Overall width: 700mm Overall height with backrest in the upright position: 1090mm"
C4	Must not inhibit reach, flexibility and dexterity of the upper torso by a substantial amount.	Millimetres (mm)	Measure the reach of user from a standard manual wheelchair and compare with reach of user from the solution	The wheelchair shall not inhibit the user's upper torso by more than 5%

Primary persona:

Figure 5: Primary persona sketch



User characteristics:

- **Name:** David
- **Role:** Primary user
- **Brief characteristics:**
    - young adult male
    - active
    - energetic
    - ambitious
    - determined/driven
- **Reason for using existing/new wheelchair:** Paraplegic
- **User values:**
    - comfort
    - maneuverability
    - convenience

Use:

- **Customer's technical familiarity and ability:**
    - Has a sense of balance and flexibility in the upper torso
    - Technical familiarity can remain limited - body controls are fairly intuitive [27] [28] "25% of [wheelchair] recipients had less than 4th grade formal education and an additional 15% were in special education" [29]
- **Frequency:**
    - Daily use apart from sleeping

Goals:

- **Goals user wants to achieve with product:**
    - Increased efficiency while performing tasks like cleaning, cooking and playing sports. [19]
    - Ability to utilize upper extremities while moving to complete tasks [19] [30]
    - Remain in control of device/wheelchair
    - Chair is sustainable and durable (not having to replace wheelchair frequently) [31]
- **Consider importance and frequency of goal:**

- High Frequency - wheelchair to become aid in everyday life and normal activity / tasks. [19]
- The wheelchair would replace current mobility device entirely

Current pains:

- Relieving David of the need to use their upper extremities (hands/arms) to control movement - thereby allowing them to complete other tasks and daily activities they were otherwise hindered from completely independently. [19][30]
- Main problems David faces are durability and stability - remove the need to have multiple wheelchairs throughout life / desire period of time. 'Customizable by User Requirement.' [19]
- All Purpose - multiple terrains. No need to change wheels (ie. gravel to grass) [19]
- The solution must reasonably be attainable for all real life scenarios - transferable between people and lifestyle. Genuine solution - trust in product and 'company'. [19]

Needs and desires:

- **Needs:**
  - Save time, efficiency, safety, durability, comfortable, Reliable [19]
  - Affordable, "Only 44.9% of recipients reported access to medical care that was both available and affordable whenever it was needed." [29]
- **Wants:**
  - Aesthetically pleasing solution, [31] reduces hand injuries and damage to clothing (clothing could get caught in the wheels or gaps).
- **Hopes:**
  - Don't feel alienated from the rest of society due to their mobility issues, "48.7% reported a negative mood state."[29]
  - Simplifying movement mechanics so that the device is usable to a broader demographic. Providing simplified instructions (picture oriented ie. ikea instructions [32]) - making the solution as accessible as possible. [33]
- **Desires:**
  - Dealing with prejudice towards wheelchair users - relieving them of some level of social anxiety and providing a sense of normality in the way that they are able to complete these tasks and live publicly.

Scenario:

David is a 23 year old former Canadian basketball player who played in the Spanish basketball league. During a late night practice, David tore his ACL putting a halt on his basketball career. David was crushed. His dreams of making the NBA were over, causing him to turn to depression and contemplate suicide. That night, David limped aimlessly across the street. As the light flickered a speeding car crashed into David causing him to go into a coma. David woke up paralized without feeling in his legs. Once again David suffered from intense depression, losing his career and physical prowess. David was now confined to a wheelchair with a very challenging task of reintegrating into society. He would frequently receive stares and unwanted attention in public while having little to no opportunities for jobs. Even in his home, David struggled to adapt to having no feeling in his legs, finding it difficult to alternate between moving his chair and performing common tasks. Even his fiery passion for basketball had seemingly flickered out, as playing in a wheelchair just wasn't the same.

However, this all changed when a mysterious visitor knocked on his door. The visitor was none other than David's basketball idol Michael Jordan. Turns out Michael was there with a sponsor; a company that produced affordable wheelchairs designed to liberate the user's hands from exclusively pushing the wheelchair. With his new wheelchair, playing basketball felt just that much more normal and natural for David. After a quick 1 on 1 session with Michael, David felt a light shine on his heart, a feeling of hope and vigour to bounce back despite all of life's challenges. David, now more determined than ever, is inspired to take back his health and life.

Secondary Persona:

Figure 6: Secondary persona sketch

User characteristics:

- **Name:** Janet
- **Gender:** Female (she/her)
- **Age:** 44
- **Role:**
    - Mother
    - Full time caregiver for parapelgic son Matthew age 15
- **Brief Characteristics:**
    - Janet has been married to her husband for 23 years, together they have 3 boys.
    - They are a white, middle class family living in a quiet neighbourhood in Waterloo, Ontario.
- **Reason for using existing/new wheelchair:** Paraplegic son
- **Values:**
    - Family over everything else
    - Independance

Use:

- Janet depends on wheelchairs to help her son navigate their house and other environments. She often has to help Matthew navigate his chair by pushing it for him.
- Janet had no familiarity with wheelchairs or with being a caregiver until her son was injured. After 3 years of experience being a full time caregiver, she is almost an expert in her context.

Goals:

- Janet wishes for Matthew to feel in control and to have more independence by investing in an electric chair.
- Janet wishes to rejoin the workforce part time and have more time to herself.

Current pains:

- On average the family spends $8000 CAD per year [34] on Matthew's disability. This includes medical bills, medications, physiotherapy and assistive devices like wheelchairs.
    - They currently have 3 wheelchairs, and it is recommended to replace one every 2-5 years [31]. Their son is not always careful and since the durability of wheelchairs declines rapidly after purchase [35] they may need to replace them sooner.
- Janet experiences many of the same psychological issues as other such caregivers[18].
    - Janet suffers from anxiety, as she feels the need to always be near Matthew out of fear that he will get hurt.
    - Janet also suffers from depression, as she feels she cannot have time for herself because she constantly needs to care for Matthew.

Needs and desires:

- Janet noticed that Matthew has developed depression from loss of role, which is very common with people living with physical disabilities [36]. His peers and siblings can move freely without a clunky wheelchair preventing use of his arms whenever he moves.
    - The ideal chair will allow him to move without the use of his hands and then hopefully Matthew will start to regain his character.
    - Janet wishes for a chair that Matthew doesn't have to use his hands to naivate. as hands are always so dirty from pushing his wheelchair. Janet is tired of getting him to wash his hands so often. [30]
- The ideal chair should be electric, as this will allow Matthew so he can regain his independence and be able to maneuver more easily, allowing Janet more time to herself and the ability to rejoin the workforce.
- Janet's family cannot afford the most high end of electric chairs in this stage of life, which can be upwards of $21 000 [20]. Their ideal chair has to be under $8000 and last longer than the average chair.

Scenario:

Janet had to stop working her dream job as a marketing consultant when her second son, Matthew aged 15, got into a car accident at the age of 12 suffering a spinal cord injury resulting in paraplegia. Janet has been a full time caregiver for Matthew for 3 years now and wishes to rejoin the workforce part time. However, she feels she cannot because Matthew has difficulties maneuvering in his standard wheelchair. The family tried searching for wheelchairs to help with Matthew's dilemma - and found Omeo. However, the family cannot afford to invest in such an expensive wheelchair at this time.

QFD and Pairwise Comparison Overview:

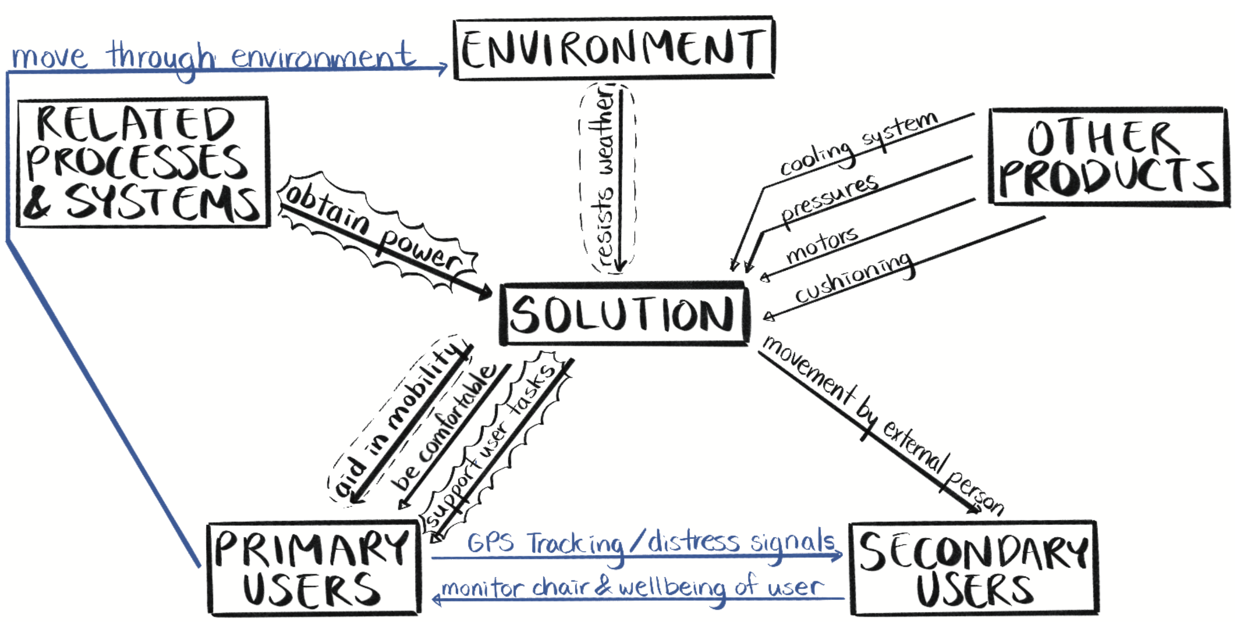
Table 5: QFD and Pairwise Comparison Overview Chart*

QFD (Engineering Requirements)	Pairwise Comparison Chart
Should be efficient: 18.7%	Should be efficient: 4
Should be affordable by comparison: 12.8%	Should be affordable by comparison: 1
Should have quick responses (break time): 14.9%	Should have quick responses (break time) (R3): 3
Should be durable (crash test): 16.9%	Should be durable (crash test) (R4): 5
Should be durable (weather test): 10.1%	Should be durable (weather test) (R4): 6
Should be lightweight: 8.9%	Should be lightweight (R4): 0
Should be comfortable: 6.5%	Should be comfortable(R5): 2
Should be user-centric: 11.2%	Should be user-centric(R6): N/A

*The figure above shows a comparison between the importance of each requirement in one column for the QFD analysis and in the other for the Pairwise Comparison Chart.

Function systems diagram:

Figure 7: Functions systems diagram



Morphological chart:

Table 6: Morphological chart

Basic Functions	Secondary Functions	Possible Means			
F1. Aid in mobility of user	SF1-1. Move Longitudinally	User's forward and backward leaning, controlled by backrest.	Control with the user's non-dominant elbow or forearm. Pressing down on a lever to make it go forward and clicking a switch to make it go backwards.	User's head forwards and backwards tilting.	User's forward and backward movement corresponds with the leaning/position of their shoulders.
	SF1-2. Move Laterally	User's lateral leaning - Pressure sensor sensitivity is customizable - core strength dependent (user safety)	Control with the user's non-dominant elbow or forearm. Turning lever to the right or left to move in the respective directions.	User's head rotation where the lateral movement responds to which side the head rotates towards.	Lateral movement corresponds with the user's leaning 'side-to-side'. Apparatus around shoulders (design 5 idea) Bluetooth relays data to chair.
	SF1-3. Stop/ Stationary	Emergency brake on the hand, ex Toggle lock	Chair movement lock / wheel lock	'Deadzone' - range where there is no movement - must exceed threshold to allow movement	Off button
F2. Obtain power	SF2-1. Obtain power	Battery - power supply (12hrs)	Electrical outlet - charging	Solar power - supplement power throughout day	Wheelchair propelled by motor
	USF2-1. Heat / Thermal energy control (Negated by F3)	Excess heat created by mechanic pieces in wheelchair			
F3. Cooling system installation	When the user is moving - the airflow of the motion is cooling the system.	Add a cooling fan that turns on when it senses the power source is getting too hot.			
F4. Support user tasks	SF4-1. Fully controlled by user	Relieve users of the need to control wheelchair using arms	Movement is body control oriented	Built in supports to safety - wheel lock to prevent movement while completing tasks requiring user to be stationary	Built in alternative steering - small toggle to control movement by hand when the user is not able to lean for any given reason.
	SF4-2. Does not impede upper extremity freedom	Remove armrest found in conventional wheelchairs and replace with handles to grab onto.	Lower seatbelt - across users hips and legs to secure body but allow torso flexibility of movement	Reduce restriction in designs where the movement is still being controlled above waist (elbow, shoulders, head). Less wires, Bluetooth, etc.	
	USF4-1. Unwanted movement (Negated by sf1-3)	Chair moving in coordination with user's body movement against user desire.			
F5. Resists weather	SF5-1. Repel water	Treat all metal materials to be rust resistant.	All padding has is made of water-resistant fabric	All wires, batteries, motors, etc., can only be accessed through waterproof maintenance doors.	All parts parallel to the ground are slightly slanted to not collect water. (Except the seat)
	SF5-2. Resist snow and ice	Allow the user to move over snow and ice during winter	Be capable of attaching wheelchair winter tires already on the market.	Have an insulated motor and battery case which allows the safe storage and functioning parts.	The length of the wheelchair above the ground should allow the addition of winter tires.
F6. Be comfortable for user		Footrest - stability and comfort for user to secure lower extremities	Handles on either side of seat - support ability for external control	Back and seat padding - customizable to user to reduce use injury (sores) and prevent skin deterioration	Four wheels - stability of wheelchair - enables longitudinal and lateral movement by mechanical to one corner of chair when turning