# Design and Testing of a Novel Power-Assisted Wheelchair System

**by**

**Garrett Kryt**

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## Approval

| | |
|---|---|
| **Name:** | **Garrett Kryt** |
| **Degree:** | **Master of Applied Science** |
| **Title:** | **Design and Testing of a Novel Power-Assist Wheelchair System** |
| **Examining Committee:** | **Chair:** Helen Bailey<br>Lecturer |
| | **Carolyn Sparrey**<br>Senior Supervisor<br>Associate Professor |
| | **Jaimie Borisoff**<br>Supervisor<br>Research Director<br>British Columbia Institute of Technology |
| | **Siamak Arzanpour**<br>Internal Examiner<br>Associate Professor |
| **Date Defended/Approved:** | May 25, 2020 |

# Ethics Statement

The author, whose name appears on the title page of this work, has obtained, for the research described in this work, either:

a. human research ethics approval from the Simon Fraser University Office of Research Ethics

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# Abstract

A power-assisted wheelchair is a hybrid between a manual and power wheelchair that consists of an electric-assist system that can be easily mounted on a manual wheelchair. These devices have a demonstrated benefit on the health and mobility of wheelchair users. However, current power-assisted wheelchairs are not addressing all user needs, and as a result there is room for improvement. In this thesis, a novel power-assisted wheelchair system was developed using Stanford Design Thinking. Design requirements were developed using ISO 13485. Concept designs were iterated and a prototype was fabricated. The result is the NeuwDrive, a lightweight power-assist system. The NeuwDrive demonstrates novelty through the use of a right-angled geared motor and a hub design that maintains the overall wheelchair width and allows for easy removal of the drive system. The functionality of the NeuwDrive was verified in two ways. First, the performance was tested using an absorption dynamometer to measure torque and speed. The test results were within the specifications of class-leading devices on the market. The weight of the NeuwDrive is 10.2 kg, below any currently available hub-motor products. Second, a focus group with power-assist wheelchair users was conducted to collected end-user feedback. The results were favourable, with participants favouring the low device weight, removable batteries and narrow width of the NeuwDrive. The results of the testing indicate that the NeuwDrive is a novel power-assist system with potential for future development.

**Keywords**: manual wheelchair; power-assist; NeuwDrive; Stanford Design Thinking

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# Table of Contents

## List of Tables

# List of Figures

## List of Acronyms

| | |
|---|---|
| MWC | Manual Wheelchair |
| PAW | Power-Assisted Wheelchair |
| PAPAW | Pushrim Activated Power-Assisted Wheelchair |
| ANSI | American National Standards Institute |
| RESNA | Rehabilitation Engineering and Assistive Technology Society of North America |
| W | Watts |
| Km/hr | Kilometers per hour |
| ICF | International Classification of Functioning, Disability and Health |
| HF/E | Human Factors and Ergonomics |
| KE | Kansei Engineering |
| HCD | Human-Centred Design |
| SDT | Stanford Design Thinking |
| HAAT | Human Activity Assistive Technology |
| ISO | International Organization for Standardization |
| IAP | Industry Accepted Practice |
| kg | Kilograms |
| VDC | Volts Direct Current |
| Nm | Newton Meters |
| RMS | Root Mean Square |
| CAD | Computer Aided Drafting |
| WBS | Work Breakdown Structure |
| AC | Alternating Current |
| PMSM | Permanent-Magnet Synchronous Motor |
| BLDC | Brushless Direct Current |
| Back EMF | Back Electromotive Force |
| AWD | All Wheel Drive |
| CNC | Computer Numerical Control |
| ABS | Acrylonitrile Butadiene Styrene |
| SCI | Spinal Cord Injury |
| RPM | Rotations Per Minute |

# Chapter 1. Introduction: Defining a Problem

## 1.1. The MWC Power-Assist System

The 2013 Canada Survey on Disability found that there were approximately 288,880 community dwelling mobility aid users aged 15 and over, representing 1.0% of the population [1]. This group includes Manual Wheelchair (MWC) users, for whom independent propulsion can be an important part of maintaining mobility and community participation. Many MWC users struggle with propulsion for reasons including pain, low cardiopulmonary reserves, insufficient arm strength, or the ability to maintain a posture effective for propulsion [2]. In addition, previous studies have shown MWC propulsion efficiency to be between 5% and 18% [3]. When these physical demands of using a MWC begin to interfere with participation, individuals often must decide whether to continue using a MWC of convert to using a power wheelchair or scooter [4].

A power wheelchair can address many of the issues of MWC propulsion, but they are not without drawbacks. A power wheelchair is much heavier than a MWC and has a larger physical footprint (width, length, height), which in turn affects portability and mobility [4]. A power wheelchair may be perceived by the user as creating a more disabled image, and appear more obvious than a MWC [5]. Power wheelchairs are also more expensive than MWCs [6]. To address the challenges presented by manual and power wheelchairs, several technologies have been developed, including MWC power-assist systems.

A Power-Assisted Wheelchair (PAW) is a hybrid between a manual and power wheelchair that consists of an electric-assist system that can be easily mounted on a manual wheelchair. The primary goal of a PAW is to provide electrical power for propulsion that is supplementary to the user’s own pushing. PAWs are available in several different configurations such as a front-end MWC attachment, Pushrim Activated Power-Assisted Wheelchair (PAPAW), rear frame attachments, and other system types.

### 1.1.1. The Pushrim-Activated Power-Assist System

The traditional PAPAW configuration is a set of two wheels that replace the MWC user's rear wheels. A system consists of two wheels with in-hub electric motors. A battery is either mounted in the hub or on the MWC as a separate component. The PAPAW is typically controlled using a sensor-equipped pushrim. An example of a PAPAW system is shown in Figure 1.

**Figure 1: PAPAW System Example [7]**

The first PAPAWS became commercially available in the early 2000s [8]. Examples of early systems include the Alber E-Motion wheels and the Yamaha JWII (known as Quickie Xtender in the USA [9]). These systems were characterized by their large system mass, with the Yamaha JWII system adding 15.9 kilograms (kg) and the Alber E-Motion system adding 21 kg to a MWC. The Alber E-Motion system uses switched pushrims, which can be pre-set to a specific assist level regardless of input torque [10]. By contrast, the Yamaha JWII uses a force-sensing pushrim which is converted to a proportional output torque [11]. These systems were thoroughly studied in the early 2000s, with PAPAWs being evaluated for their compliance with appropriate ANSI/RESNA standards in 2008 [12], as well as studies into MWC user's perceptions and experience with PAPAWS [13], [14]. Results of these studies indicate that early PAPAWs are beneficial for reducing perceived user fatigue [13], are beneficial for traversing rough surfaces [14], and pass the ANSI/RESNA stability and strength tests [12]. Some early PAPAW systems suffered failure when subjected to ANSI/RESNA fatigue testing [12].

The introduction of the Alber Twion PAPAW in 2014 represented a continuation of the development the state of the art of PAPAW systems. The Twion is like the E-

Motion system, with each hub motor having a separate enclosed battery. In contrast to the E-Motion's switched pushrims, the Twion system makes use of force-sensing pushrims. The total mass of the Twion system is only 12 kg [15], which is the lightest PAPAW system on the market. The Twion also included more consumer-focused features compared to previous PAPAWs, such as a smartphone app and a magnetic charging system. The aesthetics of the Twion system also presented a refined design in comparison to the medical-device grey plastic of previous PAPAWs.

A pushrim as the activation controller of the power-assist system is a defining benefit of PAPAWs, since MWC users are familiar with using pushrims for propulsion and braking. Force sensing pushrim activation also provides a direct measurement of the user's input, which can then correspond to a proportional power-assist, providing more intuitive and seamless function for a MWC user. Finally, pushrim control on PAPAWs can provide forward, reverse and braking assistance, which can be beneficial for turning and maneuvering.

### 1.1.2. Joystick Controlled Power-Assist Systems

Another class of PAWs similar in product form factor but different in control and operation include joystick-operated power-assist systems. These systems consist of an electric-assist system that attaches to a MWC frame and uses a joystick for steering and power. This style of control is like a powered wheelchair but could represent a less active method of control when compared to PAPAWs. An example of a joystick controlled PAW includes the Alber E-Fix [16]. This system has very similar technical specifications to the Alber E-Motion system but forgoes the switched pushrims on the E-Motion for a joystick.

This type of joystick-controlled system presents a unique option for some MWC users as they are able to gain much of the functionality of a power wheelchair but are able to preserve much of the benefits of a MWC such as portability, light weight and maneuverability.

### 1.1.3. The SmartDrive MX2+

The SmartDrive MX2+ is an add-on electric drive system that attaches to the rear of a MWC at the camber bar via a small permanently mounted bracket. The SmartDrive uses an Omni-Wheel to allow for turning of the MWC when the system is attached. The SmartDrive weighs 6.1 kg and the latest model has a battery integrated into the motor attachment for a slim and lightweight product. The SmartDrive has the benefit of not requiring the MWC user to change their wheels when not in drive mode, but the MWC user is still required to reach around to the back of their MWC and detach the motor from the frame if they wish to remove the SmartDrive, e.g. for charging it.

**Figure 2: SmartDrive MX2+** [17]

When not powered ON the SmartDrive can freewheel and aims to maintain the feel of a conventional ultralight MWC. The SmartDrive includes a small accessory bracelet that is used to control the power-assist system. The user starts the SmartDrive by double tapping the bracelet against their pushrim. The user then performs a single tap of the bracelet on the pushrim, which causes the SmartDrive to maintain the current speed. To stop, the user taps the bracelet on the pushrim once to deactivate the motor, then grips the pushrims to slow. The SmartDrive includes an anti-rollback feature for when the power assist is deactivated on an incline, and the user manual suggests that this function cannot be used as a parking brake.

The functionality of the SmartDrive is similar to automobile cruise control in that it provides an assist after it detects an input at the bracelet and will continue to assist the user until it receives a response to stop. The SmartDrive does not decelerate when the user brakes on the rims in its regular operating mode, and for this reason the manufacturers recommend that users turn off the SmartDrive when descending a ramp or hill.

### 1.1.4. Front-end Attachments

Another class of PAW includes front-end attachments for manual MWCs. Front-end attachments consist of a single front wheel and either handlebars or handcycle cranks. The system attached to the front of the MWC, raising the casters of the MWC and turning the MWC into a three-wheeled vehicle. These systems have existed in various configurations for many years in different parts of the world. Front-end attachments borrow heavily from the technology of e-bikes, with integrated batteries, bicycle braking parts and e-bike hub motors present on most front-end attachments.

One front-end attachment available in North America includes the Rio Firefly. The Firefly weighs 10.9 kg, offers 350 Watts (W) of assistive power and a top speed of 19 kilometers per hour (km/hr). The Firefly can mount to almost any ultralight manual MWC frame. The Firefly uses a basic bicycle flat handlebar, and the user controls the amount of electric power through a handlebar mounted throttle. The Firefly is an extremely compact front-end attachment, making use of a 12.5 inch (nominal) bicycle wheel for improved maneuverability and storage.

Another range of front-end attachments includes the products from Batec Mobility. Batec makes several different configurations of front-end attachments, many of which are modeled after the functionality of hybrid or mountain bikes. A Batec system is available with either handcycle cranks for user pedaling or with a bicycle flat handlebar for pure power-assist. Batecs can be configured to provide up to 1200 W of assistive power and a top speed of 30 km/hr. Batec systems typically weigh more than 16 kg depending on configuration.

The front-end attachment is relatively new to the North American market, and therefore has not been studied thoroughly by researchers yet. One advertised benefit of front-end attachments is the fact that they raise the casters from the ground, therefore increasing the clearance of the MWC and enabling the user to access varied terrain such as grass and dirt that would normally stop a caster wheel.

## 1.2. Systems at a Glance

**Table 1: Some of the Available MWC Power-Assist Systems**

| Device | Picture | Highlights |
|---|---|---|
| Twion | <br>**Figure 3: Twion System** [7] | • Power-Assist Motors that replace regular manual MWC wheels.<br>• Requires permanent mounting bracket<br>• Pushrims sense a push and provide proportional assistance<br>• Backwards/forwards assistance<br>• System Mass: 12 kg (6 kg per wheel) |
| SmartDrive MX2+ | <br>**Figure 4: SmartDrive System** [17] | • System attaches to small bracket on camber bar<br>• Controlled by a user worn wristband<br>• No braking or backward assistance<br>• Hill-hold function stops rolling backward<br>• System Mass: 5 kg |
| E-Motion | <br>**Figure 5: E-Motion System** [18] | • Power-Assist Motors that replace regular manual MWC wheels.<br>• Requires special mounting bracket at MWC rear axle.<br>• Backwards/forwards assistance<br>• System Mass: 21 kg |
| Batec | <br>**Figure 6: Batec System** [19] | • Front-end MWC attachment<br>• Throttle control at handlebar<br>• Top speed of 9.7 m/s (35 km/hr) based on config.<br>• Attaches to permanent bracket on manual MWC<br>• System Mass: 25 kg |
| Firefly | <br>**Figure 7: Firefly System** [20] | • Front-end MWC attachment<br>• Throttle control at handlebar<br>• Top speed of 5.3 (19 km/hr)<br>• Can fit most manual MWCs<br>• System Mass: 10.9 kg |

| | | |
|---|---|---|
| Yamaha JWII/ Quickie Xtender | <br>**Figure 8: Yamaha JWII System** [21] | • Power-Assist motors that replace manual MWC wheels<br>• Separate battery that sits on backrest of MWC and connects to both hubs<br>• System Mass: 15.9 kg<br>• Top Speed of 6 km/hr |
| E-Fix | <br>**Figure 9: E-Fix System** [22] | • Powered rear wheels with separate battery and joystick<br>• Turns manual MWC into compact electric MWC<br>• System Mass: 19.3 kg<br>• Top speed of 6 km/hr |

## 1.3. Benefits of MWC Power-Assist Systems

The benefits of PAPAW systems have been well documented. In a systematic review in 2013, Kloosterman et al. stated that:

> The pros of power-assisted MWC propulsion are: reduction of load on the arm, decrease in cardiopulmonary demand, increase in propulsion efficiency, maintained benefit of exercise, easy access to challenging environments and - compared to a powered wheelchair - relatively lightweight and easy to transport [9].

In the review Kloosterman highlighted that measuring daily activities on a test track showed that carpet, dimple strips, ramp and curb are significantly easier to complete with power-assist [23]. In another study the power-assisted MWC seemed easier for tasks which required more force, such as curbs, irregular surface and ascent/descent [24].

Kloosterman et al. (2013) noted that transition from hand-rim MWC to another type of mobility device, such as a powered wheelchair, is chosen because of arm injury, pain, insufficient arm strength, low cardiopulmonary reserves or inability to maintain posture. Based on the results of the systematic review, a PAW could have an effect on all these factors, except the ability to maintain posture [9]. Therefore, a PAW could have the potential benefit of delaying the transition to a power chair for a MWC user.

In a study with 15 MWUs with tetraplegia who completed a 4-wk trial with and without a power-assist device, the MWC users recorded significantly faster travel times in comparison to manual MWCs [25]. A different 16-wk study with 20 full-time MWC users found that they traveled significantly further and to travel beyond their usual daily distance when using the power-assist system [26]. Participants in a qualitative study commented that the PAW was much easier to push than their manual chairs, allowing them to go further and faster [14]. This increased ability to wheel long distances enabled users in one study to participate in novel activities such as going to the mall; “I went to the mall once, that I guess I wouldn’t have went if I didn’t have the wheels” [13]. Traveling further and faster present two potential benefits of PAW that could have an impact on community participation and independence for MWC users.

One positive user perception of PAWs is its benefits for traversing inclines and other physical barriers. Users have indicated that power-assist is needed to compensate for the barriers of the built environment, such as ascending inclines, travel across side slopes and rough terrain [27]. Giesbrecht et al. found that MWC propulsion enabled participants to increase their level of community mobility and access new environments compared with using their manual MWC. In particular, managing inclines/ramps was identified as an important achievement, as well as propelling over softer surfaces, such as grass or carpet [14].

Users also indicated that power-assist is beneficial for combatting tiredness and fatigue related pain. Ramirez and Holloway wrote that: “Power assistance is also needed at the end of the day when tiredness is experienced. One participant said: “I struggle with having to propel my MWC for long distances. After 2 hours you can notice aches and pains” [27]. 16 of the 20 participants in a study performed by Giacobbi et al. reported general decreases in fatigue after using a power-assist MWC for a total period of eight weeks in their lived environment [13].

In a scoping review of propelling aids for MWCs, it was generally found that propelling aids had a positive impact on activity participation, function and personal factors. The review did not completely distinguish between powered (e.g. PAPAWs, SmartDrive) and non-powered (e.g. handcycles, specialized MWC handrims), but noted that among the reviewed papers on power-assisted propelling aids, “Pushrim-Activated Power-Assisted MWC” (PAPAW) was the most cited (n=37 manuscripts; 22.7%) [28].

One interesting outcome of the scoping review of propelling aids included the application of the International Classification of Functioning, Disability and Health (ICF) to classify the outcomes of the reviewed literature. As stated by Choukou et al; :The use of the ICF, a widely used conceptual framework, helps situate propelling aids according to function and influence on the user, and allows for comparisons to be made between propelling aids based on similar criteria [28].” The three most frequently documented sub-domains of the ICF included “Activity & Participation”; Body Function, Neuromusculoskeletal & Movement-related”; and “Personal factors/Occupation Perception”. Use of these sub-domains in this study seemed to indicate that power-assisted propelling aids are beneficial in all of these sub-domains. Continued evaluation of newly researched PAWs using the ICF framework could yield a reinforced understanding of the benefit of PAWs.

## 1.4. Drawbacks of MWC Power-Assist Systems

### 1.4.1. Documented Drawbacks from the Literature

Some of the documented cons of power-assisted MWC propulsion are: difficulty performing tasks which require greater control such as a wheelie, difficulty with car transfers and access to home environment due to additional weight and width compared to a hand-rim MWC, unknown long-term effects on physical fitness and the possibility of repetitive motion injuries to not have time to heal because of the power-assist. [9]

The increased mass of a PAW system leads to a larger rolling-resistance, and inertia during start-up [29]. Kloosterman et al. in 2016 concluded that the additional power delivered by the motor (a prototype system in that study) is already enough during start-up to provide an additional biomechanical advantage on shoulder load compared to propulsion without power-assist [30]. Therefore, to overcome the mass of a PAW, the system must provide enough power to overcome the retarding forces of its own mass to provide significant benefit to the MWC user.

Every reviewed qualitative paper on MWC power-assist indicated that device weight was an important factor in usability [13], [14], [27], [31]. Users rightly point out that it is expected that accessory devices for MWCs should not increase the weight of their MWC to the extent that they cannot propel the MWC with the device turned off [27],[14].

PAWs have also been documented as having a negative effect on the speed and ease of car transfers [13]. In another study, the car transfer, which required taking off and putting on the wheels, was not possible for 50% ($n = 5/10$) of the subjects when using the power-assisted MWC [3]. In a study with eleven full-time, community dwelling MWC users, Cooper et al. found that all subjects completed the car transfer faster with their personal MWCs than with the PAW [8], and determined that significant differences ($p<0.05$) were identified for both taking the PAW wheels off and putting them back on again. Furthering this evidence. Guillon et al. found that subjects completed faster car transfers with their manual MWC compared with a PAW system and theorized that this difficulty in removing and installing the PAW system is partially a result of the increased system mass, which in turn slows car transfers [31].

Every PAW currently on the market increases either the width or the length of the MWC in some dimension. In the case of PAPAW wheels, the width of the MWC is increased, which can make negotiating doorways and turns more difficult in comparison to a manual MWC [24]. An increase in MWC width when a power-assist system is installed has been indicated by users to be a contributing factor to this decrease in maneuverability [9]. In the case of the SmartDrive or a front-end attachment, the length of the MWC is increased. This is of importance in regard to front-end attachments, which can negatively impact the turning radius of the MWC by lengthening the wheelbase through the addition of the single front wheel.

Another design feature of some PAWs that impacts maneuverability includes difficulty coordinating pushes of equal force on each wheel in handrim-sensored power-assist systems. Karmarkar et al. evaluated three PAPAWs and identified that PAPAWs are quite sensitive to the force applied to the pushrims and are more difficult to manipulate than MWCs in conditions that need higher skills and coordination, such as making a turn and parking [12]. In a qualitative study with eight users, Giesbrecht et al. reported from users that the inability to successfully coordinate pushes of equal force resulted in the power-assist system turning or moving erratically [14].

One downside of all currently available PAW is that they require an additional bracket or clamp to be mounted permanently to the MWC. This is problematic from a product design standpoint as a proprietary bracket cannot fit every model of MWC frame. In addition, the brackets add complexity, weight, cost and another point for failure on the MWC frame. Users have expressed that an ideal PAW would attach to their current and favorite MWC easily, while preserving its width and appearance [27]. Elimination of a permanent mounting bracket for an attached PAW could therefore present an opportunity for preserving a MWCs functionality and appearance.

Finally, users have expressed frustration with the feeling of PAW systems when switched OFF and still attached to the MWC frame. The system could either be OFF during slow-speed maneuvers if the battery is fully drained. The PAW system in OFF can affect the difficulty of pushing the MWC through the added system mass [27] or through increased resistance from the PAW drive components. One YouTube reviewer describing the SmartDrive as feeling like a “tractor tire” when switched OFF [32].

### 1.4.2. Power-Assist and the Nature of Manual MWC Propulsion

Research people who use ultra-lightweight wheelchairs has shown that everyday life activities are dominated by short bouts of starting, stopping and turning [33]. In addition, it is established that regardless of surface type, greater propulsion force and torque are needed for users to start pushing the MWC from a dead stop compared with maintaining a constant self-chosen pace [34].

PAPAWs can be effective in reducing shoulder load and force generation in the extremes of shoulder motion during start-up [30].The study used an instrumented pushrim activated power-assist MWC and motion capture systems to analyze the forces applied to the pushrim and the kinematics of the shoulder during start-up and constant velocity pushing. They were able to show that peak forces and moments were 1.6 to 2.0 times higher during start-up than velocity propulsion (independent of electric assist), as well as demonstrate a decrease in mechanical loading of the shoulder for anterior, posterior and inferior directed forces and abduction and extension moments when using the power-assist [30].

However, some previous versions of PAWs have been found to be of little help during start-up. A study in 2017 found that user pushrim propulsion force was not significantly larger when using the SmartDrive MX1 (a previous version) and that there was no difference in single-push startup speed [35]. This indicates that the SmartDrive MX1 may have been completely missing the most needed component of power-assistance, during the start-up phase of propulsion.

From the previously described evidence it is established that the greatest dynamic propulsion requirement for a MWC user is in the start-up phase of pushing. It is also shown that a PAW can reduce the force generation during start-up [30]. Therefore, the potential may exist for system mass reduction if the PAW that focused on delivering small bouts of power-assist. The theoretical goal with this system would therefore be to be able to provide high peak torque, at the expense of long-distance continuous operation. A drive system of this type would help to eliminate the described high-force pushing scenarios that may result in injury [30].

## 1.5. A Methodology for Solving Design Problems

The engineering design process has traditionally broken user requirements into functional and non-functional aspects. Functional requirements refer to the technical details of a system's characteristics, properties and parameters, while non-functional requirements cover all constraints that reflect the needs of Human Factors and Ergonomics (HF/E) [36]. The traditional engineering design approach is to primarily solve the technical problems defined by the functional requirements, and to optimise these solutions under the constraints of the non-functional requirements [37]. A problem with the traditional engineering approach is that insufficient consideration of HF/E when creating functional requirements can lead to unsatisfactory design [38], as well as require costly modifications to a design when HF/E needs are only considered in the late design phase [36].

The benefits of incorporating HF/E needs into the design process at the problem definition phase are numerous. Consideration of HF/E needs can improve user experience and system performance [36]. Incorporating additional design constraints derived from HF/E needs in the early design phase also helps to limit the size of the design solution space, making a design problem clearer and easier to solve. This can also reduce the number of required design iterations, which is beneficial to the entire design process [39]. Many different design methodologies for integrating human factors into engineering design exist. Two design methodologies that are used for conceptual engineering design include Kansei Engineering (KE) and Human-Centred Design (HCD).

### 1.5.1. Kansei Engineering

Kansei Engineering emerged in Japan during the 1970's as a customer oriented approach for new product development [36]. KE is also known as affective engineering in North America [40]. KE considers customer's feelings and emotions from the early design process with the purpose of bringing satisfaction to the customer by converting customer's emotions to measurable and physical design parameters based on ergonomics and computer science [36], [41]. Japanese corporations such as Mazda, Toyota and Honda have used Kansei with great market success. KE has also been used in industrial case studies such as refrigerator design [42] and aesthetic design of smartphones [43]. However, KE also has some limitations regarding the indefinite definition of customer's emotions, the comprehension of Kansei words, and the difficulty in translating user's emotion verbalisations into the design (Steinberg, Tursch, and Woll 2015).

### 1.5.2. Human-Centred Design

Human-Centred Design (HCD), which can be synonymous with user-centred design, is a series of design methodologies that use an approach where the design process focuses around understanding how users can, want or need to use a product, rather than compelling a user to change their behaviour to accommodate a product [36]. One methodology of user-centred design is Stanford Design Thinking (SDT).

SDT is a product of d.school, a division of Stanford University founded in 2005 that is recognized as a thought leader in HCD [44]. SDT is made up of five modes; empathize, define, ideate, prototype and test.

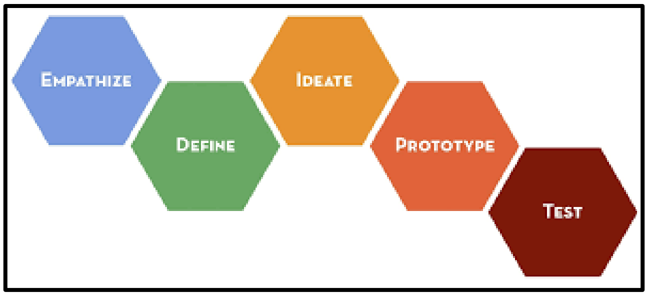


**Figure 10: The Five Modes of Stanford Design Thinking, Licensed under CC BY-NC-SA, Author: Hasso Plattner Institute of Design at Stanford University** [44]

The empathize mode consists of understanding people, within the context of your design challenge. An important component of the empathize mode includes the ability to empathize with people by learning their values, with the best solutions resulting from the best insights into human behaviour. The define mode is where the designer brings clarity and focus to the design space; to make sense of the information gathered in the empathize mode. The result of the define mode is the problem statement. This is a clear concise statement that places the design problem in the context of a user and specific needs. The ideate mode is where the designer develops concepts and ideas based on the information gathered in the previous modes. These concepts are then developed further in the prototype mode, where prototypes are created to increase understanding of the design space. The final mode is the test mode, where the prototype is evaluated, ideally with end users to gain feedback for future iterations. Iteration is a fundamental of good design, and is an integral part of SDT. At the end of every mode, the designer should assess whether or not they should move the project into the next mode [44].

One conceptual model used to guide assistive technology provision in rehabilitation includes the Human Activity Assistive Technology (HAAT) model. The four core concepts of the HAAT model include: the human, the activity, the assistive technology and the context. The culmination of a human performing a functional activity using an assistive device within a given context is defined as the assistive technology system [45]. HAAT has been predominantly used as a tool for research in the assistive technology field, with researchers integrating HAAT into research study backgrounds, study designs and interpretation of findings [45]. The HAAT model shares many similarities to the ideate mode of SDT, with an emphasis being placed on observing the human, activity and assistive technology interaction within the specific context. For this reason, SDT could be thought of as an extension of HAAT with a focus on the actual development of assistive technology, instead of just research and evaluation.

SDT has been used as a design framework successfully in assistive technology and medical device development. For instance, SDT was used by General Electric Healthcare in the development of a children-friendly Magnetic Resonance scanner [46], The Jefferson Health Design Lab in the creation of a unique pediatric pain scoring system called CareCube [47], and the development of NightScout, a cloud-based diabetes management system developed by patients for patients [48]. SDT has also seen success in academic research and development. For example, a human-centred design thinking approach has been applied to a course at the MIT D-Lab on creating low-cost prosthetic and assistive devices for the developing world, with the result being a 60% continuation of the student projects after graduation [49].

Based on the demonstrated use of Stanford Design Thinking in assistive technology development, its emphasis on user feedback throughout the design process, and the ability to easily understand and adapt SDT to a variety of design projects, SDT was chosen as the guiding design methodology for this project. The following section lays out the thesis in the context of SDT.

## 1.6. Scope of Thesis

The results of the empathize mode are presented in the motivation and review of current literature (Chapter One). The design mode is encompassed by the problem statement at the end of Chapter One, and the creation of design requirements, which is the focus of Chapter Two. Chapter Three includes the ideate mode where concepts were developed from the design requirements, and also documents the prototype mode, where a prototype was fabricated. Chapter Four includes the test mode, where the prototype was evaluated for qualitative performance through a focus group and for quantitative performance though physical testing. Chapter Five summarizes the project outcomes and recommends future work.

## 1.7. Problem Statement

Power-assisted wheelchairs have a demonstrated significant benefit on the health and mobility of manual MWCs users [9]. However, as the literature review has shown, current MWC power-assist systems are not addressing all potential user need, and as a result there is room for improvement. For example, the user is restricted in their regular chair operation when the power-assist system is attached but OFF. Installing and removing currently available systems is difficult, because of device form factor and high system mass. In addition, a perceived market need may exist for a purely power-assist device where the primary focus is pushing force reduction, rather than driving without pushing. Focusing on full driving capability may have led to an overdesign of current power-assist MWC systems, which results in excessive system mass. Any potential for a reduction in mass of power-assisted MWCs should be a benefit for active user scenarios, such as MWC transfers into a vehicle. Based on these identified opportunities, the objective of this thesis was to design a power-assisted MWC system that incorporates the ability for a MWC user to easily remove the device with one hand, maintains MWC width (i.e. form factor), and seeks to optimize the overall power to system mass ratio for active MWC users. Secondary objectives were to benchmark the performance of existing PAW systems and work with end users to explore their responses to PAW systems and the proposed design solution.

# Chapter 2. The Define Mode: Generation of Design Requirements

## 2.1. Introduction

The International Organization for Standardization (ISO) develops and publishes International Standards. These ISO standards seek to lay out best practices for making products, managing processes and delivering services. Some benefits of using an ISO process for a design project include a better understanding of customer needs, reducing risk and liability, and developing a greater demand and acceptance for new products.

The development of medical devices requirements is formalized in ISO 13485 (Medical Devices), which includes a quality management system and the necessary requirements for regulation of the medical technology. A key component of the ISO 13485 quality management system is the generation of design requirements. The design requirements must present a set of measurable, attainable objectives for a design through which concepts can be evaluated. The design requirements also represent an extension of the problem statement by including engineering specifications. Using ISO 13485 methods for the development of design requirements in the SDT design methodology allows for clear documentation of the user needs and their translation into attainable engineering goals.

A specific area of complexity in the creation of the design requirements involved the definition of the torque, speed and power characteristics of a PAW. Defining the specific performance criteria and to understand how these criteria translate into user experience are critical for defining effective design requirements for a new PAW.

## 2.2. Methods

### 2.2.1. ISO 13485 and Design Requirements

In consultation with the British Columbia Institute of Technology's MAKE+ Applied Research department, an ISO 13485:2016 certified research group, a quality system procedure for the development of design requirements was applied to the design problem of creating a novel PAW. The quality system highlights that design requirements could consider the following areas:

**Table 2: Quality System Highlights**

| |
|---|
| Client specifications |
| Previous or similar designs |
| Patents and patent applications for similar ideas |
| Use Cases for specified or intended use |
| Applicable statutes, regulations, and standards |
| Function, performance, and safety |
| Design and development |
| Manufacturing and Sales volumes |

The quality system procedure also outlines how to record the design requirements. The procedure says that the records of the design requirements should be:

**Table 3: Design Requirements Procedures**

| |
|---|
| Unambiguous |
| Simply stated |
| Single-topic |
| Not in conflict with other requirements |
| Verifiable |
| Uniquely numerically identified |
| From a defined rationale and /or source |

With the procedure in place, the design requirements were developed. The complete table of design requirements is shown in Table 4 on the following page. The requirements are split into three sections; overall, technical and functional requirements. In keeping with ISO 13485, each requirement includes a rationale, the source of the requirement, and a method of verification. Examples of sources of design requirements for this project included MWC user feedback, literature review, and Industry Accepted Practice (IAP).

**Table 4: Complete Design Requirements Table**

| Category | Number | Design Requirement | Rationale | Source | Verification Criteria | Verification Method |
|---|---|---|---|---|---|---|
| Global | 1.01 | Must maintain width of conventional MWC | Indicated as a problem in available systems | Literature Review | Measurement | Measure width with system on MWC |
| Global | 1.02 | Must fit a variety of MWC designs | Increases compatibility and potential adoption | Literature Review | Observation/Team Consensus | Demonstrate on several MWCs |
| Function | 2.01 | System can drive forward/reverse | Assist is needed both ways | Literature Review | Observation | Drive system forwards and backwards |
| Function | 2.02 | Batteries must be easily removed and installed | Allows user to customize range, charge one battery or another | Literature Review | Functional Test | Demonstrate functionality of swapping batteries |
| Function | 2.03 | Wheel must allow for 24, 25, 26 inch rim sizes | Allows for fitting system on most chair sizes | IAP | Observation/Team Consensus | Use a standard MWC rim during prototyping |
| Function | 2.04 | Wheel must use a pneumatic tire | Pneumatic tires have lower RR, are lighter and more comfortable | IAP | Observation/Team Consensus | Observe tire in system, confirm valve works |
| Function | 2.05 | Wheel must have a conventional MWC axle | Readily available, compatible with standard MWC receiver dimensions | Literature Review | Observation/Team Consensus | Observe axle in system |
| Function | 2.06 | Wheel must be removable with one hand | Impossible to grab Twion diameter comfortably with one hand | Observation | Observation/Team Consensus | Observe operator remove wheel |
| Technical | 3.01 | PAW must attain 2.5 m/s) 9 km/hr | Same top speed as SmartDrive and Twion | IAP | Measurement | Run system on dynamometer |
| Technical | 3.02 | Continuous output torque of 21 Nm per wheel | Based on kinematic analysis of system requirements/product benchmarking | Analysis | Measurement | Tests on dynamometer |
| Technical | 3.03 | Must weigh less than 5.7 kg | SmartDrive system is lightest on market at 5.7 kg | Literature Review | Observation/Team consensus | Measure mass of system |
| Technical | 3.04 | Output power of 60 W per wheel | Based on kinematic analysis of propulsion | Analysis | Measurement | Dynamometer testing |
| Technical | 3.05 | 20 km range | Based on other devices on market | IAP | Measurement | Dynamometer testing |
| Technical | 3.06 | System runs on 36 V DC | Compatibility with electrical systems | IAP | Functional Test | Check battery voltage |

### 2.2.2. Design Requirements from Problem Statement

The global design requirements included the requirements from the problem statement that were a result of PAW user feedback and initial product research. The global design requirements are summarized in Table 5.

**Table 5: Overall Design Requirements**

| Category | Number | Design Requirement | Rationale | Source |
|---|---|---|---|---|
| Global | 1.01 | Must maintain width of conventional MWC | Indicated as a problem in available systems | Literature Review |
| Global | 1.02 | Must fit a variety of MWC designs | Increases compatibility and potential adoption | Literature Review |

Requirement 1.01 states that the drive system must maintain the width of a conventional MWC. This requirement was developed from the initial project literature review and was included in the problem statement. The verification criteria for this requirement includes the measurement of the width of the MWC with the PAW installed and with a regular manual wheel installed to determine if the PAW has increased the overall chair width.

Requirement 1.02 states that the drive system must be compatible with a variety of MWC designs. This requirement stems from the problem statement and is in reference to the requirement for all PAWs to have some type of permanent anti-torque bracket mounted to the MWC frame.

The configuration and design of MWC frames is extremely varied with almost no standardization, and as a result PAW manufacturing companies are forced to design and stock many different brackets to allow their systems to be compatible. Some resellers of PAW systems such as the Batec even publish compatibility lists to inform purchasers if their MWC is compatible [50].

It can be a large undertaking for a product designer to engineer for universal compatibility from the outset. However, the need for a PAW to be compatible with a variety of MWC frame designs will increase its marketability and adoption. Therefore, the need for the system to be compatible with a variety of MWC frames had to be documented as a design requirement from the outset to avoid designing a system that was too specific. The proposed verification criteria for this requirement includes demonstrating how the PAW is installed on a test wheelchair frame with a description of how this functionality could be adapted to other wheelchair frames.

### 2.2.3. Functional Design Requirements

After the basic requirements from the problem statement had been defined, a series of functional requirements were established to provide a basis for establishing a criterion for the human-device interaction. The functional requirements were all developed through team discussion and first-hand MWC user feedback. The complete list of functional design requirements is shown in Table 6.

**Table 6: Functional Design Requirements**

| Category | Number | Design Requirement | Rationale | Source |
|---|---|---|---|---|
| Function | 2.01 | System can drive forward/reverse | Assist is needed both ways | Literature Review |
| Function | 2.02 | Batteries must be easily removed and installed | Allows user to customize range, charge one battery or another | Literature Review |
| Function | 2.03 | Wheel must allow for 24, 25, 26 inch rim sizes | Allows for fitting system on most chair sizes | IAP |
| Function | 2.04 | Wheel must use a pneumatic tire | Pneumatic tires have lower RR, are lighter and more comfortable | IAP |
| Function | 2.05 | Wheel must have a conventional MWC axle | Readily available, compatible with standard MWC receiver dimensions | Literature Review |
| Function | 2.06 | Wheel must be removable with one hand | Impossible to grab Twion diameter comfortably with one hand | Observation |

Requirement 2.01 defines the driving characteristics of the proposed PAW system, stating that the drive system must be able to provide power-assist in forward and reverse. This requirement resulted from a PAW user expressing disappointment due to the lack of assistance from their PAW when moving the wheelchair in reverse [27]. In addition, the Twion system incorporates reverse-assist [15]. The proposed verification for this requirement is to drive the system in forward and reverse upon completion of the prototype.

Requirement 2.02 states that the batteries of the proposed PAW system must be easily removed and installed. This requirement arose from the user interviews conducted by Ramirez and Holloway where MWC users described their ideal power-assist system, which included a battery that “can be separated from the device for air travel. In this way, backup batteries can fit into a backpack” [27]. Having removable batteries could also allow for the user to have two separate batteries, e.g. one at work and at home, so that the user would never be caught without a charged battery. The proposed verification criteria for this requirement is a test demonstrating the ability to swap batteries. The requirement to remove batteries in this stage of the design process focuses primarily on the hardware required to allow battery swapping, and does not address ergonomics or other human factors.

MWC wheels are available in several sizes, commonly referred to by their nominal diameter of 24, 25 and 26 inch. MWC users might select a MWC wheel diameter based on personal preference or the concept that an increase in wheel diameter can result in a decrease in rolling resistance [51]. As a result of the availability of multiple wheel size for MWC users, functional requirement 2.03 states that the proposed PAW system must allow for 24, 25 and 26 inch wheel sizes.

The rationale for this is that different wheel sizes will allow for more user choice. Rear and front mounted PAW systems can accommodate different wheel sizes, but traditional PAPAWs such as the Twion system are limited to 24 inch wheels. The proposed verification criteria for this requirement is to incorporate a standard MWC rim and tire during the design process. This idea is borrowed from bicycle technology, where different wheel diameters are attained using different rim diameters and corresponding spoke lengths, while the hub dimensions remain the same throughout diameters.

Two main tire constructions exist for MWCs; pneumatic and solid tires. Solid tires are more durable and flat-resistant when compared to pneumatic tires [52]. Pneumatic tires offer lower rolling resistance than solid tires [53], which can have an effect on the physical strain of steady-state MWC propulsion [54]. With the proposed PAW system being focused on active MWC users, functional requirement 2.04 states that the system’s wheel must have a pneumatic tire. The proposed verification for this is to demonstrate the installation of a pneumatic tire on the system.

Requirement 2.05 states that the proposed PAW system must have a conventional MWC axle. MWC axles for ultralight MWCs are available in 12.7 millimeter (mm) and 12 mm diameters, with the vast majority being the 12.7 mm size [55]. The Twion system makes use of a conventional MWC axle and a torque bracket, allowing for easy installation of either the powered Twion wheels or conventional MWC wheels. The Twion system is shown in Figure 11.

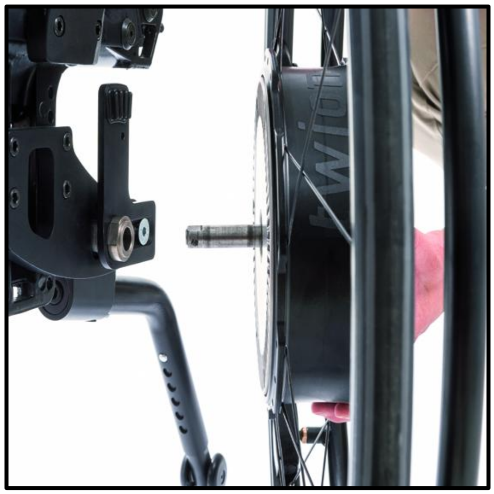

**Figure 11: Twion Axle and Torque Bracket** [56]

The rationale for this requirement is that using a conventional MWC axle will allow for widespread compatibility of the PAW device on different MWC frames. This requirement provides more functional detail to the overall requirement 1.02 which states that the system must fit a variety of MWC designs. The proposed verification method for this design requirement is to demonstrate the installation of the device in a standard 12.7 mm axle receiver to ensure compatibility.

A functional challenge established from the user feedback and literature review in Chapter One included the difficulty that MWC users have with car transfers when using a PAW system. In a car transfer a MWC user is required to lift every component of their MWC into the vehicle. This can be difficult for heavy, bulky objects such as PAW systems. Figure 12 shows an independent car transfer process: The user first transfers into the vehicle from their MWC. They then remove one wheel at a time and lift them over their body into the vehicle. Finally, they pull the MWC frame over their body and into the vehicle.

**Figure 12: Car Transfer Example Source: YouTube, Author: Josh Brunner** [57]

The SmartDrive system provides some ergonomics for car transfers by including a handle on the device. By contrast the Twion system is much more difficult to remove than the SmartDrive system. The user must lift a 6 kg wheel off the MWC frame while pressing the inner axle detent button, a task which appears challenging to impossible with only one hand. In addition, the Twion system cannot be gripped or placed on the force-sensing pushrims. This makes care transfers with the Twion system very difficult and room for improvement in the ergonomics of PAW systems exist.

As a result of this identified need, functional requirement 2.06 states that the wheel of the proposed PAW device must be removable with one hand, similar to the functionality of a MWC wheel. This will allow for easy installation and removal of the PAW when car transferring or disassembling the MWC. The proposed verification criteria for this requirement is to demonstrate removing the wheel with one hand.

### 2.2.4. Technical Design Requirements

After the overall and functional requirements from the problem statement had been defined, a series of technical requirements were established to provide a basis for engineering design decisions. Some of these technical requirements were established by analyzing the specifications of available systems, while others had to be established and verified through engineering analysis. To create these requirements, a dynamic analysis was performed for a variety of MWC power scenarios. An absorption dynamometer was fabricated to provide a means for verifying the future prototype in relation to the design requirements, as well as perform physical benchmarking of two popular (particularly for active users) PAW systems available on the market; the Alber Twion and the SmartDrive MX2+. The complete list of technical design requirements is shown in Table 7.

**Table 7: Technical Design Requirements**

| Category | Number | Design Requirement | Rationale | Source |
|---|---|---|---|---|
| Technical | 3.01 | PAW must attain 2.5 m/s (9 km/hr) | Same top speed as SmartDrive and Twion | IAP |
| Technical | 3.02 | Continuous output torque of 21 Nm per wheel | Based on kinematic analysis of system requirements/product benchmarking | Analysis |
| Technical | 3.03 | Must weigh less than 5.7 kg | SmartDrive system is lightest on market at 5.7 kg | Literature Review |
| Technical | 3.04 | Output power of 60 W per wheel | Based on kinematic analysis of propulsion | Analysis |
| Technical | 3.05 | 20 km range | Based on other devices on market | IAP |
| Technical | 3.06 | System runs on 36 V DC | Compatibility with electrical systems | IAP |

Requirement 3.01 refers to the top speed of the proposed PAW system. For the system to be competitive with the current state-of-the-art, the top speed of the proposed PAW was selected to be 2.5 m/s (9 km/hr). This is within the same top speed range as the SmartDrive (2.5 m/s or 8.9 km/hr) [58] and the Twion (2.7 or 9.7 km/hr) [15] systems. The proposed verification for this requirement was to measure the top speed of the PAW with speedometer-type device during a driving test.

Requirement 2.03 states that one side of the drive system must weigh less than 5.7 kg. This requirement stems from the original problem statement where it was determined that any reduction in mass of a PAW system can be a benefit. The target mass of 5 kg was selected based on the SmartDrive mass (5.7 kg) and the Twion system (6 kg per side). The proposed verification for this requirement is to weigh the entire system with a calibrated scale.

The design requirement describes one side of the system being less than 5 kg to account for the fact that the Twion system is two wheels and therefore adds 12 kg total to the mass of the MWC. It was not decided at this stage of the design process if the proposed PAW system would have a two-wheeled layout such as the Twion or a single-wheeled layout such as the SmartDrive, therefore the design requirement is written to reflect that any single side should weigh less than 5.7 kg, to minimize the impact of the device on car transfers and set a low target mass.

Requirement 3.05 establishes a range of 20 km for the proposed PAW system. This range was determined for the proposed PAW to be competitive with the available systems. The quoted range of the SmartDrive in the device's technical specifications is 19.8 km [58] and the quoted range of the Twion system is 13-21 km [15]. The proposed verification is based on the testing protocol used to test PAW systems, which consists of applicable tests from the American National Standards Institute (ANSI) and Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) MWC testing standards [59]. The test for theoretical range of a device is described by Rentschler et al.:

> The MWC was driven at maximum speed around a 54.5-m test track 10 times in each direction. A watt-hour meter was connected between the MWC battery and drive motors. This device measured the ampere-hours used by the MWC. The following equation was then used to determine the maximum theoretical distance of the MWC:
>
> $$R = \frac{(C \times D)}{(E \times 1000)}$$
>
> Where R is the theoretical range in kilometers, C is the capacity of the battery in ampere-hours at a 5-hour rate of discharge as declared by the battery manufacturer, D is the total length of the test track in meters, and E is the electric charge in ampere- hours used during the test [60].

The verification process will apply this test to the PAW system prototype to quantify the distance range.

Requirement 3.06 proposes a nominal voltage of 36 Volts Direct Current (VDC) for the proposed PAW system. The rationale for this value is based on the availability of batteries and controllers in 36 Volt configurations for electric bicycles. The verification process for this requirement will be to check the battery voltage with a voltmeter.

### 2.2.5. Defining Torque and Power Requirements

Technical design requirements 3.02 and 3.04 specify values for torque and mechanical output power of the proposed PAW system. These values present a challenge to quantify for design requirements because they are related to physical values such as terrain, slope and user mass. Variations in terrain such as sand, dirt and grass impact the rolling resistance of the MWC, potentially increasing the propulsion torque requirement. An increase in the slope of the driving surface requires a greater propulsion torque to overcome the impact of the gravitational force from ascending the ramp. Finally, an increase in user mass impacts the propulsion torque required to accelerate the MWC and user.

Quantifying the torque and power requirements of the proposed PAW system becomes increasingly important in reference to the problem statement, which highlighted the fact that a need may exist for “a purely power-assist device where the primary focus is pushing force reduction.” This is important a first step in determining performance requirements for the proposed PAW system might be to investigate the technical specifications of available systems. However, if the market opportunity is to build a system that is theoretically lower powered (and therefore ideally lower mass) than available systems, then the specifications of currently available systems may provide overestimated starting points for the design requirements. In addition, existing PAW manufacturers may not be accurately quoting their specifications or leaving out pertinent information to completely describe the performance of their devices. As an example, the available mechanical performance information from the technical specifications for the SmartDrive and Twion systems is highlighted in Table 8.

**Table 8: Power and Torque Specifications**

| | SmartDrive MX2+ | Alber Twion |
|---|---|---|
| Output Power | 250 Watts | 2x60 Watts |
| Output Torque | No quoted torque | 2x20 Nm (from manufacturer) |
| Top Speed | 2.5 m/s (8.9 km/hr) | 2.7 m/s (9.7 km/hr) |

The specifications in Table 8 gives some clues as to the torque and power requirements of a lightweight PAW system, but do not give a clear picture of use case performance. The specifications also appear to have conflicting information such as the fact that the SmartDrive has more than double the output power of the Twion, though the devices both have a similar top speed. Based on this initial research, it became clear that further analysis was required to properly determine the torque and power requirements for the proposed PAW system.

The driving torque at the rear wheels can be calculated using kinetics equations. Figure 13 shows a free body diagram of the forces acting on the rear wheel of a MWC while driving up a slope

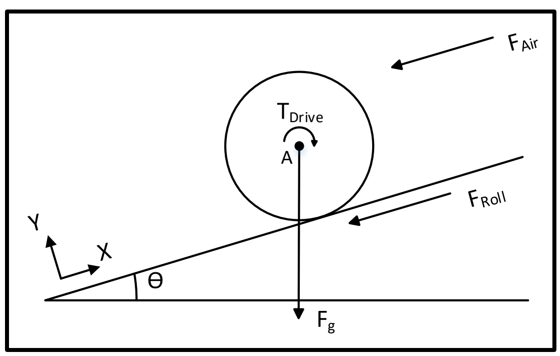


**Figure 13: MWC Rear Wheel Free Body Diagram, Source: Own Work**

Based on no slip at the rear wheel, the driving torque $T_{Drive}$ can be rewritten as:

$$T_{Drive} = F_{friction} \times r_{wheel}$$

**1**

The resulting sum of the forces for a MWC accelerating up a slope is:

$$\sum F_x = 0 : \; m \times a = \; F_{friction} - F_{Roll} - F_{Air} - F_g \times \sin\theta$$

**2**

With the following list of variables:

**Table 9: List of Variables**

| | | |
|---|---|---|
| $T_{Drive}$ | = | MWC driving torque |
| $F_{friction}$ | = | Force of friction counteracting drive torque |
| $R_{wheel}$ | = | Radius of rear wheel |
| $m$ | = | Mass of the MWC user/chair/PAW |
| $a$ | = | Acceleration |
| $F_{Roll}$ | = | Force of rolling resistance from rear wheels |
| $F_{Air}$ | = | Force of air resistance |
| $F_g$ | = | Force of gravity |
| $\theta$ | = | Angle of slope |

Three test cases were analyzed using inputs for equation 2 and solving for $T_{Drive}$ from equation 1. In order to do this some assumptions had to be made. The radius of a 25" nominal MWC wheel is 0.305 meters. The combined mass of the user and MWC was set at 150 kg, based on the specified user & MWC mass for the SmartDrive and Twion systems. The 100 kg ($95^{th}$ percentile person) test dummy is also the most commonly used in MWC testing [61], therefore a mass of 150 kg provides some safety factor and accommodation of the MWC's mass. The estimated acceleration of the MWC is 0.5 meters/second$^2$, based on the specifications of the SmartDrive system, which quoted a maximum acceleration of 0.6 meters/second$^2$ [58].

Rolling resistance on a MWC is impacted by the surface of the ground and its contact with the MWC tires, the bearing friction of the wheel bearings as well as the inflation,material properties and diameter of the tire [62]. Air resistance is a function of the MWC frontal area and velocity. The rolling resistance force and air resistance force were lumped into a single resisting force of 10 Newtons based on published aerodynamic data for MWCs [63]. This is a reasonable assumption based on the published data and may even overestimate the value based on the fact that the test MWC in the study was a folding MWC frame and may not have as optimized rolling resistance/aerodynamic properties as an ultralight manual chair. The ramp angle $\theta$ was set at 4.8 degrees based on American Disabilities Act Standards for ramps [64].

Wheel inertia was ignored in this analysis because of the impact of the masses mechanical components that were not known at this stage of the design process. In addition, the values of rotational inertia for some wheelchair wheels can vary from 0.117 $kgm^2$ to 0.154 $kgm^2$. With an estimated wheel angular acceleration of 1.64 $rad/s^2$ based on a MWC linear acceleration of 0.5 $m/s^2$ and using equation 3, the torque from inertia can be estimated at 0.253 Nm, which is reasonable to neglect at this stage because the geometric properties are not known.

$$T_{Drive} = I_{wheel} \times \alpha \quad (3)$$

The system was also assumed to be a two-wheel hub motor style system such as the Twion, and the calculated values are the peak torques for one hub motor (e.g. total propulsion force divided in half). The results of the analysis are summarized in Table 10.

**Table 10: Peak Torque of one wheel based on analysis**

| | Slope Acceleration Condition | Flat Ground Acceleration Condition | Cruising up ramp (No Acceleration) |
|---|---|---|---|
| Peak Torque (Nm) | 31.7 | 13.0 | 20.3 |

These results were in the range of the Twion system's quoted torque of 20 (Newton Meters) Nm. An important factor in interpreting the acceleration numbers is to recognize that the torque calculated is the peak torque for an electric drive (e.g. the torque for acceleration). The cruising up ramp torque represents the continuous torque. The peak torque is only output intermittently, while the continuous torque is the consistent operating point of the device.

In order to incorporate the large peak torque and the smaller continuous torque into a single value, the Root Mean Square (RMS) torque was calculated for a trapezoidal move profile shown in Figure 14. The RMS calculation takes into account not only the varying amounts of torque that are needed during operation, but also the amount of time for which each torque must be produced. The result is a torque value that, if produced continuously by the motor, would yield the same level of motor heating as all the various torques and durations encountered by the motor during its duty cycle [65].

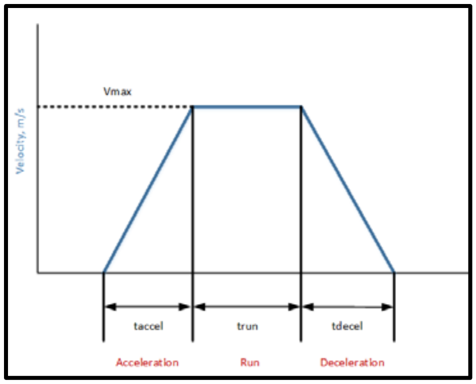


**Figure 14: Trapezoidal Move Profile, Source: Own Work**

The move profile was applied to the scenario where a PAW was accelerating on a ramp to a constant velocity and then stopping, as this was determined to be the highest torque scenarios based on Table 10. Equation 4 shows how to determine the RMS torque.

$$T_{RMS} = \sqrt{\frac{{T_{accel}}^2(t_{accel}) + {T_{run}}^2(t_{run}) + {T_{decel}}^2(t_{decel})}{t_{accel} + t_{run} + t_{decel} + t_{idle}}} \quad (4)$$

The idle time ($t_{idle}$) in this case was unknown, so was set to 0.0 seconds to calculate the absolute worst-case RMS torque. The acceleration time $t_{accel}$ was set to 1.11 seconds to reflect the time required to accelerate to 0.83 m/s (3 km/hr) up the ramp. This value was deliberately selected to be lower than the proposed top speed of the system because the speed of the system could acceptably be slower up a ramp than on flat ground, due to the increased torque requirement from going up a ramp. If the system were designed to accelerate up a ramp to a speed of 2.5 m/s (9 km/hr), it could end up being overbuilt (and therefore an increased mass) for flat ground moving. This is demonstrated by the values in Table 10, where the flat ground acceleration torque is only 41% of the ramp acceleration torque. In addition, the median velocity in a study of people using MWCs in daily life during typical bouts of mobility is 0.43 m/s [33], indicating that the ramp speed estimate of 0.83 m/s could be conservatively fast. An overestimate in the early design phase is reasonable, because of the neglecting of factors like efficiency, temperature change and inertia in the early stage calculations.

The time to decelerate $t_{decel}$ was calculated based on the natural deceleration rate of the ramp, which requires no deceleration torque $T_{decel}$, was set at 0.94 seconds, based on deceleration from 3 km/hr to 0 km/hr. The acceleration torque $T_{accel}$ was set at 31.7 Nm and the running torque $T_{run}$ was set at 20.3 Nm. The run time $t_{run}$ was set at 10 seconds to represent driving up a ramp. Based on these inputs, the resulting RMS torque was calculated to be 20.8 Nm. This result for the RMS torque seemed realistic based on the specified torque of the Twion system and the input case scenarios selected for the calculation and was thus used as technical design requirement 3.02.

Once the proposed continuous output torque was determined, a continuous power was calculated using equation 5.

$$P = T \times \omega$$

**5**

The power P was calculated by multiplying the torque T by the wheel's angular velocity. The value for the RMS torque was used for T and the angular velocity was based on a 0.3049 m radius wheel (25" nominal) at 0.83 m/s (3 km/hr). The resulting continuous power was calculated to be 57.0 Watts, which was rounded to 60 Watts for the design requirement.

To confirm that the selected values for design requirements 3.02 and 3.04 would work for other driving conditions, the torque and power required to accelerate for the same trapezoidal move profile, but this time moving on flat ground from 0.0 m/s to 2.5 m/s (9 km/hr) were calculated. The idle time ($t_{idle}$) in this case was unknown, so was set to 0.0 seconds to calculate the absolute worst-case RMS torque. The acceleration time $t_{accel}$ was set to 5.55 seconds to reflect the time required to accelerate to 2.5 m/s (9 km/hr). The run time was set at 21 second, the value of the median bout of mobility of users of MWCs as found by Sonenblum et al. [33]. The acceleration torque $T_{accel}$ was set at 13.0 Nm and the running torque $T_{run}$ was set at 1.53 Nm, based on a 10 N combined rolling resistance/aerodynamic retarding force. Based on these inputs, the resulting RMS torque was calculated to be 6.27 Nm. This result for the RMS torque seemed realistic as the driving torque on flat ground should be much lower than on a ramp. The resulting continuous power requirement for the system on flat ground was calculated to be 51.4 Watts for one wheel.

These calculations indicate that the system should perform satisfactorily on ramps and flat ground. The ramp test case also gives an indication of the system's ability to perform on carpet or rough terrain, where the torque requirement will also be higher than on flat ground.

### 2.2.6. Construction of a PAW Dynamometer

In order to verify the technical design requirements pertaining to the mechanical output torque, speed and power of the PAW system a method had to be devised to measure these quantities under controlled test conditions. One technique of measuring work and power of an electric motor or MWC user is to use an absorption dynamometer [66]. An absorption dynamometer uses a braking element coupled to the driven rolling element and provides a braking torque that resists the output of the device being measured. MWC dynamometers consist of a braking element attached to a roller. The MWC's rear wheels are placed on the roller and the torque, speed and power are measured from the MWC user's pushes or drive motors.

For verification of the PAW prototype system, a dynamometer was needed to specifically measure the output torque and power of the electric drive system, without the input of the user. During investigation of the literature for the design requirements, it was found that research had been done with Pushrim Activated Power-Assisted Wheelchairs (PAPAWs) and MWC users to investigate the benefit to MWC users. Specifically, Cooper et al. [3] in 2001 tested a Yamaha JWII PAPAW on an absorption dynamometer and found that with the PAPAW the user had a significantly lower oxygen consumption and heart rate with the PAPAW when compared with a manual MWC at different speeds. Other studies furthered this work and user mechanical efficiency was higher when using the PAPAW [67], and that PAPAWs reduced energy demands, stroke frequency and range of motion for subjects with tetraplegia [68]. However, no one had compared the output characteristics of PAW systems without users, in a manner like the published dynamometer data of torque, speed and power that is available for industrial electric motors.

Therefore, it was determined that an absorption dynamometer should be constructed for two functions: (1) To provide a means for future verification of the proposed PAW system in comparison to the technical design requirements, and to (2) benchmark currently available PAW systems to establish torque, speed and power characteristics for these devices. Benchmarking would in turn provide some verification of the assigned values of torque, speed and power in the technical design requirements before proceeding to the ideate mode of the design process.

## 2.3. Benchmarking of Power-Assist MWC Systems

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### *INTRODUCTION*

A power-assist MWC system is a hybrid between a manual and power MWC that consists of an electric-assist system that can be easily mounted on a conventional manual MWC [9]. The past decade has seen an explosion in the development of new power-assist MWC systems. This market growth, coupled with the demonstrated significant benefit of power-assist on the health and mobility of manual MWCs users [9] means that research in this field of technology is timely and will reveal more about how power-assist systems benefit MWC users and how new designs can address potential limitations of existing products.

Two recent systems that have garnered substantial industry support are the SmartDrive MX2+ and the Alber Twion power-assist wheels. With the advent of these products on the market, the potential for research to characterize the mechanical properties of these devices exists. Specifically, the torque, speed and power of these systems in various loading conditions is not known beyond the basic information provided by the device manufacturers. An example of this might be how the SmartDrive MX2+ performs on a section of steep hill with different weight users. Understanding the electromechanical characteristics of these systems is important for several reasons, including:

1) Providing a better understanding of the benefit of power-assist to the MWC user. A study in 2016 concluded that available pushrim-assisted power-assist systems

are effective in reducing shoulder load and partly effective in reducing force generation in the extremes of shoulder motion during start-up [30]. Characterizing the electromechanical output of these power-assist systems will provide insight into their ability in different loading scenarios, such as climbing a slope or other high-torque situations.

2) Matching system performance to user needs. This is important in the design of power-assist systems as the system mass has been shown to be a significant detriment to the MWC user because it increases the total mass of the chair [9], therefore requiring more propulsive force when the system is not providing assist and increasing the difficulty of tasks such as car transfers. Investigating the mechanical output of these systems and matching this data to user feedback could yield insight into real and perceived performance of power-assist systems for future improved designs, perhaps including the design of lighter systems.

3) The verification of analysis concerning the power, torque and speed requirements of a power-assist system. To improve power-assist systems, we need to characterize current product capabilities, and have the tools for development benchmarking when iterating new design solutions.

The purpose of this study was therefore to verify the functionality of a laboratory MWC dynamometer and to benchmark the electromechanical performance characteristics of the SmartDrive MX2+ and Alber Twion systems under a range of torque and speed conditions.

## ***METHODS***

### Dynamometer

Absorption dynamometers are used to absorb and record energy from a rotating input by varying the amount of load applied to the input through a braking element. To characterize the energy provided by the power-assist systems and the resulting MWC dynamics at a range of torque and speed settings, an absorption dynamometer was designed and manufactured (Figure 15).

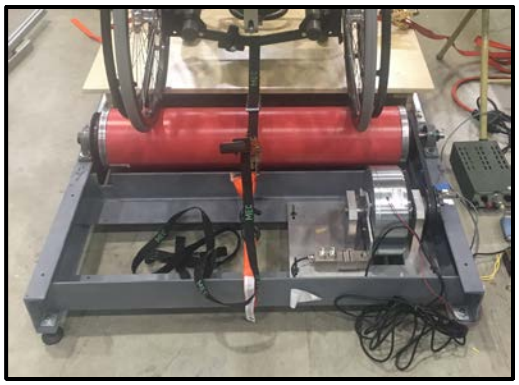

**Figure 15: Absorption Dynamometer, Source: Own Work**

A hysteresis brake (Magnetic Technologies Ltd. EB-1750M-2DS) was used as the absorption unit. The brake was coupled to a roller where any power-assist system and MWC can be installed and tested. A Hall Effect sensor (Littelfuse 55505) and frequency-to-voltage converter (Texas Instruments LM2907) were used to measure the roller speed, while a load cell (Anyload 563YH, A2A Amplifier) and torque arm were used to measure the torque. The two inputs were recorded using a data acquisition device (Measurement Computing USB-1208 FS). The data was sampled at 750 Hz for both channels.

### ***Power-Assist System Background***

While the SmartDrive MX2+ and the Alber Twion can both be classified as power-assist systems, the nature of their assist differs substantially. The SmartDrive MX2+ provides a constant velocity assist for a prolonged duration, regardless of user force input on the pushrims. The SmartDrive MX2+ is controlled using a separate accessory wristband.  The user double taps the wristband to start ramping up the speed. They then tap to coast at the current speed and then double tap to stop [69]. The result is a control method that functions well for instances where the user requires prolonged power-assistance, such as traversing a city block or carpeted hallway.

In contrast, the Alber Twion wheels act more as a direct push-assist device, using sensing pushrims to provide additional assistance once a user push has been detected. The result is a dynamic power-assist that essentially amplifies a user's push. For the Twion to attain the same type of long distance continual power-assist similar to the SmartDrive, the user must continually push the pushrims to maintain velocity, similar to pushing without assist.

The difference in assist types necessitated different testing methods for each system. The SmartDrive was tested using testing methods similar to conventional electric motors, where the steady-state speed and torque are recorded for discrete intervals to form a graph of the continuous output speed, power and torque. Since the Twion cannot output a continuous power due to its dynamic functionality, the Twion was tested over a range of torques at the same discrete braking torque values as tested for the SmartDrive. A researcher pushed the Twion wheels by providing input to the pushrims in a manner analogous to conventional wheeling. The different testing methods necessitated different procedures, processing filters and post-processing, which is detailed in the following sections.

### *SmartDrive Testing Procedure*

The SmartDrive was installed on a test MWC and the drive wheel of the SmartDrive was located on the dynamometer roller. The maximum speed setting was used for all testing (5.5 mph). The SmartDrive was accelerated to the constant maximum speed at no braking torque. The recorded torque at this no-load condition includes the resisting torque from the dynamometer friction. The dynamometer braking torque was then increased in approximately 2 Nm increments up to 10 Nm measured at the roller. The SmartDrive increased its torque output to overcome the braking torque, which resulted in a decrease in output speed. The speed was settled to a steady-state value after every torque increase, resulting in discrete steady-state measurements for multiple torque and speed values. This process was continued until the maximum torque of the hysteresis brake was applied.  A total of ten tests were performed with the SmartDrive using this method.

The results of the SmartDrive testing were processed using a low-pass 2nd order Butterworth filter with a cut-off frequency of 1 Hz and then downsampled to 1 Hz (Matlab, Mathworks Inc). The mechanical output power of the SmartDrive was then computed by multiplying the torque and velocity. A linear regression was performed on the torque vs. speed data, based on the presence of a linear proportional relationship of these variables for a brushless DC motor [70].

### *Twion Testing Procedure*

Both wheels of the Alber Twion system were installed on a test MWC and the wheels were located on the roller of the dynamometer. The testing started with a zero-braking torque input. The researcher was seated in the test MWC and pushed the Twion pushrims five times, at which point the braking torque was increased to by approximately 2 Nm incrementally up to 10 Nm measured at the roller. Five pushes were conducted at each torque increment for a total of 30 pushes per test. The Twion speed and output torque were recorded for each resisting torque setting.

The results of the Twion testing were processed using a low-pass 2nd order Butterworth filter with a cut-off frequency set at 40 Hz. The angular acceleration was then calculated using the angular velocity data and numerical differentiation in MATLAB. The torque from system inertia was then computed by multiplying the inertia and the angular acceleration. The inertial torque, measured torque and friction torques were then summed to compute the final motor output torque.

## *RESULTS*

### SmartDrive Results

The results of the SmartDrive testing are shown in Figure 16 and Figure 17. The SmartDrive achieved a peak torque of 14.2 Nm at 170.8 RPM, resulting in a peak power of 253.0 Watts (values of torque and speed presented in Figure 16 & Figure 17 are measured at the 7.5 inch diameter SmartDrive wheel). The maximum torque value corresponds to a maximum linear propulsive force for a MWC user of 148.9 N at 6.1 km/hr. At approximately 10.5 Nm of torque output the linear torque speed relationship of the SmartDrive changes, which is shown by the line in red in Figure 2. This change ultimately limits the motor output to a maximum of approx. 250 Watts, which is the quoted maximum power of the SmartDrive system [3].

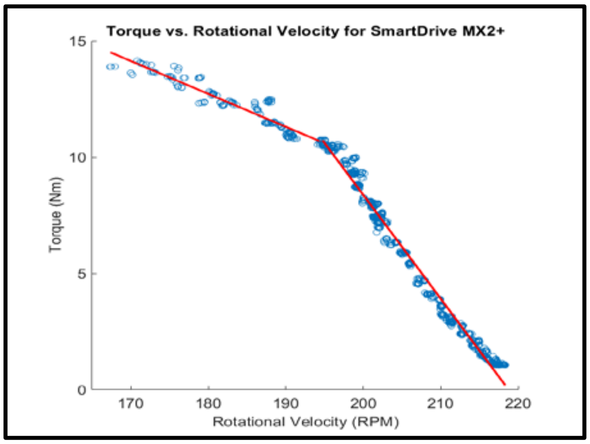


**Figure 16: Torque vs. Rotational Velocity for SmartDrive MX2+, Source: Own Work**

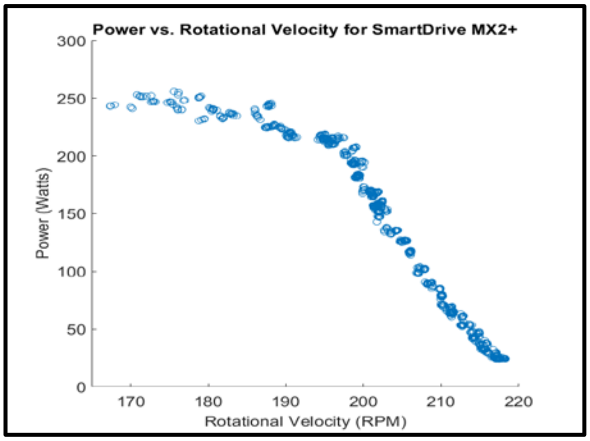


**Figure 17: Power vs. Rotational Velocity for SmartDrive MX2+, Source: Own Work**

**Twion Results**

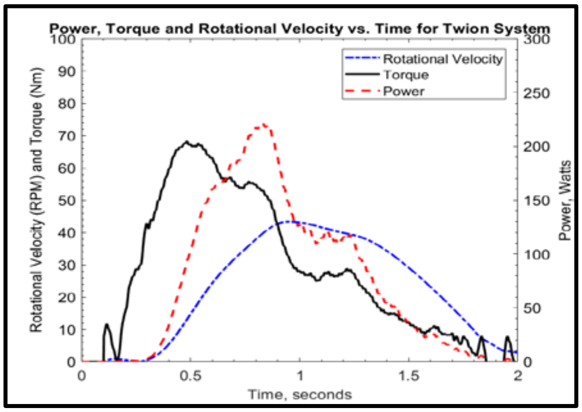


**Figure 18: Power, Torque and Rotational Velocity vs. Time for Twion System, Source: Own Work**

Figure 18 shows the results of the Twion testing when a resisting torque of 7 Nm was applied to the system at the roller. The plot shows a large input torque before the speed changes, a result of the user's input push. At 0.5 seconds the rotational speed is increasing and the torque is decreasing while the peak power is observed. This is the region where power is being supplied by the user and the Twion. At one second there is minimal change in the rotational speed and relatively constant torque and power. The power at this point is 120 Watts combined for both wheels, in-line with the reported power output of the Twion system [5], indicating that the Twion is the main source of propulsion. The Twion output torque at this point is approximately 28 Nm, when considering both wheels together. This torque corresponds to an equivalent linear propulsive force of a MWC user of 94.1 N at 4.5 km/hr.

## *DISCUSSION*

The results of this testing demonstrate that the calibrated hysteresis brake dynamometer can be used to test MWC power-assist systems under a variety of loading scenarios. The preliminary benchmarking completed in this study provides information about the performance of the SmartDrive and Twion power-assist systems and highlights the substantial differences in functionality in these systems. The performance characteristics captured in this study can now be used to further inform dynamic analysis into the theoretical performance requirements of a power-assist system, e.g. a 100 kg person with a 20 kg MWC pushing up a slope of 6° at a speed of 4 km/hr requires approximately 175 Watts of continuous power.

In the case of the SmartDrive, the results of the testing show that the device is designed to output relatively high power through a large range of speeds and torques. For example, the SmartDrive can output greater than 10 Nm of torque from 150 RPM to 190 RPM. This means that the SmartDrive can output greater than 100 N of propulsive force for constant forward speeds less than 6.8 km/hr, translating to significantly beneficial assistive power in scenarios such as hills or sloped surfaces. For perspective, the data indicates that the SmartDrive is able to propel a 100 kg user with a 20 kg MWC up a 4.8° concrete ramp at approximately 7 km/hr. The SmartDrive's ability to operate at greater than 200 watts for a significant portion of its high-torque operating curve in Figures 2 & 3 indicate that the device is especially well designed for power output in high torque scenarios such as climbing hills and steep grades. However, the SmartDrive system power may be limited in its assistive effects by its inherent design using its own weight to generate traction in certain situations, e.g. slick surfaces or loose ground [3] although this was not tested here.

The results of the Twion testing confirm the device's capability for intended use as a power-assist device. The user of the Twion must always engage the device with a torque input before receiving power. This means that the peak torque of 70 Nm in Figure 4 is the sum of two components, the user input torque and the Twion assistive torque. The torque at this peak could indicate that the user in high torque scenarios such as starting on a hill must push hard before receiving assistive power. This could also be a result of the Twion using force-sensing pushrims [5] which would require a large force input on an incline due to the increased propulsion requirement. In contrast, the Alber E-Motion power-assist system uses pushrim sensing, but provides a fixed level of assist regardless of the magnitude of user force input [31]. Based on the results of this study, the Twion system can supply assistive power for high-torque scenarios such as an incline, but requires continued user input with proportional force to maintain propulsion. For reference, the Twion system can provide a propulsive force equivalent to a 100 kg MWC user with a 20 kg MWC pushing up a 4.8° concrete ramp at a speed of 3 km/hr.

The verification and deployment of the dynamometer system resulting from this study will additionally allow for the testing of many types of power-assist devices. Resisting torques based on real-world conditions such as sloped ramp can be input to the system to see how it performs under load. Additionally, torque requirements based on user and MWC mass could be tested by varying the input braking torque. An example of this might be to quantify variations in the SmartDrive performance on a MWC ramp for a 150 lb and a 300 lb occupant. Battery life testing also presents another potential area for research with the dynamometer. Additionally, the dynamometer presents a method for testing prototypes of power-assist systems, using repeatable input conditions, and allows for benchmarking potential prototypes against currently available systems.

## *CONCLUSIONS*

A hysteresis brake dynamometer was manufactured and used to benchmark two power-assist systems, the SmartDrive MX2+ and the Alber Twion. The results of this study show that both power-assist systems meet their expected output torque and power specifications, and the dynamometer recorded output torque, power and speed of the power-assist system under test. The testing confirmed that the SmartDrive is a high-power system, well suited to high torque and speed applications; and the Twion is a very responsive power-assist system, providing assistive torque in response to a user's pushrim input. The resulting data from this study can be used to further inform dynamic analysis for the design of future power-assist systems, and the dynamometer can be used to test these systems under a range of loading conditions appropriate for real-world mobility situations.

## *ACKNOWLEDGEMENTS*

This research was completed with contributions from the Rick Hansen Institute, the Natural Sciences and Engineering Research Council of Canada, MITACS and the Canada Research Chairs.

## 2.4. Chapter 2 Conclusion

Chapter 2 encompasses the define mode of the project. Building upon the problem statement, a series of design requirements were created using the procedures from ISO 13485 (Medical Devices). The resulting requirements and problem statement provide a clear set of verifiable parameters that allow the project to move into the next phase of SDT; the ideate mode.

The design requirements can be broken into three sub-requirements, which included overall, functional and technical requirements. The requirements draw from user feedback, technical specifications, team discussion and engineering analysis. Each requirement includes a rationale and verification criteria.

To perform the future verification of technical design requirements, an absorption dynamometer was fabricated. The absorption dynamometer allowed for performance benchmarking of two PAW systems; The Alber Twion and the SmartDrive MX2+. This benchmarking used unique testing that eliminated the impact of user input and analyzed the mechanical and electrical characteristics of the devices. Results of this study indicated that the calculated estimations of the mechanical torque, speed and power selected for the technical design requirements were within the range of a lightweight, low-power PAW system.

# Chapter 3. The Ideate and Prototype Modes: Design and Prototyping of the NeuwDrive Wheelchair Power-Assist System

## 3.1. Introduction

To begin the ideate mode of the project a work breakdown structure was created in the ideate mode to define each component and sub-component of the prototype. The work breakdown structure is a tool outlined by the Project Management Institute for defining the scope of a project [71] This allowed for multiple concepts to be generated for each sub-component. Several of the sub-components had clear solutions that were primarily a function of rigid design requirements, while other sub-components were heavily co-dependent and required significant idea generation. When sub-component concepts were defined, the project transitioned from the ideate mode to the prototype mode.

The prototype mode is defined by the iterative generation of artifacts intended to answer questions that move towards a final design solution [44]. The prototype mode is highlighted through iteration, with the final output being a working physical prototype that is ready for testing. A Computer Aided Drafting (CAD) model in SolidWorks was generated in the early stages of the prototype mode to develop the sub-component integration and design layout. The CAD model underwent over 20 iterations until a satisfactory concept was finalized. Upon completion of the model, a physical prototype was manufactured, completing the prototype mode of the project.

### 3.1.1. The Work Breakdown Structure

The Work Breakdown Structure (WBS) is shown in Figure 19. Application of the WBS broke the system down into five categories. These categories were meant to be general so as not to impact the ideation of each component. For example, the drivetrain category acknowledged the need for a drive system but did not bias a direct-drive versus geared system solution. Each of the five main categories were necessary components for the function of the PAW system.

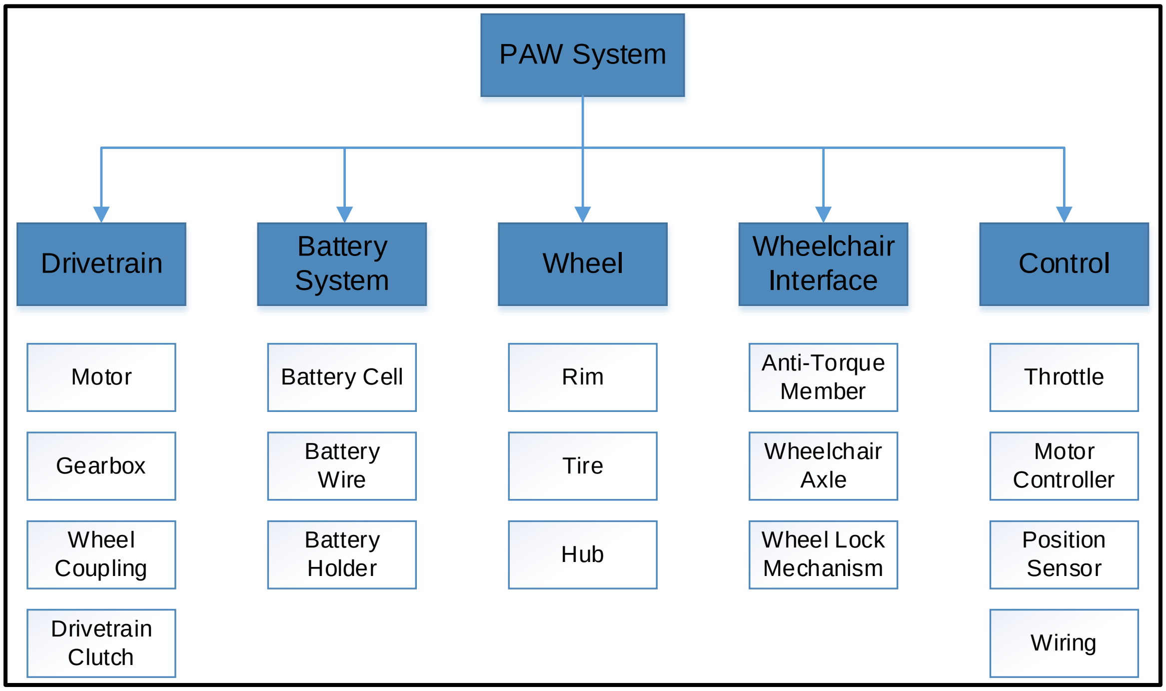


**Figure 19: Work BreakDown Structure, Source: Own Work**

Each main category is broken up into sub-categories that highlight necessary design tasks for a complete system. The sub-categories were developed based on the design requirements. For example, the ability of the system to transmit torque necessitates some type of anti-torque mechanism on the wheelchair interface. The following section details the concept development for each category and sub-category.

## 3.2. Concept Development

### 3.2.1. System Cost

The SmartDrive MX2+ retail cost is approximately $6,000.00 USD depending on retailer [17], and the Alber Twion system is approximately $6,700.00 USD depending on retailer [56]. All other PAW systems available on the market are priced in this range. The goal with all assistive technology is to develop products that can be affordable for the end user, but the product must also be competitively priced. From a prototyping perspective, it is best to prototype with inexpensive, off-the-shelf components to test concepts. The 1-3-9 rule of thumb for designing for cost states that the manufacturing cost is the manufacturing cost is approximately three times the cost of the materials. Also, the selling price is approximately nine times the material cost, or three times the manufacturing cost [72].Therefore the target fabrication cost was set at $1,000 CAD for the first prototype iteration, based on a $8500 CAD retail price.

### 3.2.2. Drivetrain Design

The drivetrain of the proposed PAW system was broken into five sub-categories; motor, gearbox, wheel coupling and drivetrain clutch. It was established from the design requirements that the system would use a 36 Volt electric motor, but a decision had to be made about the type of motor and the use of a direct-drive vs. geared motor. This choice was captured in the sub-categories through the inclusion of a motor and gearbox sub-category. The design requirements stipulated that the system must allow for the wheel to freewheel, which was captured in the sub-categories through the inclusion of drivetrain clutch. A drivetrain in this case referred to a mechanical means to couple and uncouple the drive system from the output. The wheel coupling sub category referred to the need for some way to couple the output wheel to the drive system.

#### *Motor Sub-Category*

It was established from the design requirements that the proposed system should run on 36 VDC. This eliminated any Alternating Current (AC) motor from the selection process. Available DC motors to choose from included brushed motors, brushless switched reluctance motors, Permanent-Magnet Synchronous Motors (PMSM) and

Brushless DC (BLDC) motors [73] each have strengths and weaknesses for the proposed context.

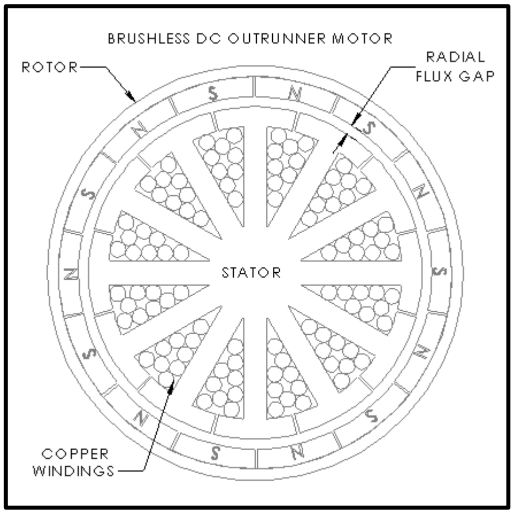


**Figure 20: Brushless DC Motor Cross-Section, Source: Own Work**

**Figure 21: Example DC Motor, Turnigy Multistar Multi-Rotor. Source: Own Work**

A cross-sectional diagram of a brushless DC motor is shown in Figure 20. The motor depicted is an outrunner, a sub-type of BLDC motor where the rotor is the outer rotating portion of the motor. The permanent magnets are attached to the rotor, while the stator is made up of steel sections that are wrapped with copper wire windings. The radial flux gap is the radial distance between the rotor and stator. Figure 21 shows a DC motor with magnets, copper windings, rotor and stator visible.

The DC brushed motor is robust, easy to control provides a high torque and is inexpensive. The brushed DC motor uses carbon brushes to mechanically couple the rotor and stator of the motor. However, because the carbon brushes sit on the commutator of the rotor, they are subject to constant wear from the rotation of the commutator [74]. In addition, commutator and brushes limit the maximum speed, efficiency and overcurrent capabilities of the motor [73]. Finally, the brushes can cause sparking through the rotor coils as the brushes cross the insulating gaps between commutator sections [74]. For these reasons, the brushed DC motor does not represent a good choice for a power-assist system, as the carbon brushes represent significant limiters on the performance of the drive system in key areas such as efficiency, current capability and longevity.

The switched reluctance motor is a type of brushless motor with a high torque output that is fault-tolerant and very robust because of its concentrated windings. They are capable of withstanding significant temperatures, and are used in jet engines and starters [74]. However, the switched reluctance motor has an inherent pulsating torque ripple (a small residual torque that appears as a “ripple” on an oscilloscope) [73], as well as a lower torque density (torque per unit volume) than PMSM and BLDC motors [74]. These two characteristics make the switched reluctance motor unsuitable for a power-assist system, where a smooth torque output and highest possible power density are desirable.

PMSMs and BLDC motors are extremely similar in construction and function, with the primary difference being that PMSMs have a sinusoidal back electromotive force (back EMF) and BLDCs have a trapezoidal back EMF as a result of different rotor coil windings. The back EMF is the induced voltage (or current) in the rotor coil that results from the rotor coil being driven to rotate inside the magnetic field. This back EMF acts counter to the supplied drive current and is a function of the driven speed of the motor [75]. Note that current and back EMF are inherently linked in this case through Ohm’s Law.

The key performance differences between PMSM and BLDC motors include power density, torque per unit current, drive simplicity and speed range. If the copper losses (the current lost in the copper windings during excitation) and the frame size of a PMSM and BLDC motor are equal, the BLDC motor will have 15% more power density. This also means that for a same given speed, the BLDC motor will have a 15% higher electric output torque [73]. This made the BLDC motor the preferred choice for a power-assist drive system based on power density, a metric that is important because a high-power density will result in a lighter, more powerful drive, all other motor parameters being equal.

Torque per unit current is another important metric because a high torque per unit current allows for smaller power control circuitry, which lowers the cost, complexity and heat generation in the system [73]. Comparing PMSM and BLDC motors that have the same value of peak back EMF, the torque per unit current is up to 33% higher in the BLDC motor. This results from the shape of the current waveform in the BLDC motor, which is rectangular, in comparison to the sinusoidal waveform of the PMSM motor [73]. Therefore, the BLDC motor was the preferred choice for a power-assist system based on torque per unit current.

Looking at existing power-assist systems, it was found that the almost all available systems use a BLDC motor. In addition, the electric-assist bicycle market and hobby remote-control device market have seen an explosion in the availability of inexpensive, easily controlled BLDC drive and motors. BLDC motors are also more affordable than PMSM  Based on the describe benefits of BLDC motors and their almost ubiquitous use in industry at present, a BLDC motor was proposed as the primary drive motor for the system.

### ***Direct Drive and Geared Motors***

With the selection of a BLDC motor for the drive system, the next design decision was to determine if the application was suited to a direct drive motor or a geared motor.

A direct drive motor does not include a gearbox and builds the hub shell of the wheel directly onto the rotor of the motor. Since the hub shell of the wheel is directly coupled to the rotor and the tire, the rotor of the direct drive motor must rotate at the required angular velocity ($\omega$) of the wheel. The mechanical output power of the direct drive motor is governed by equation 5 from chapter two:

$$P = T \times \omega$$

**5**

Where $\omega$ is the angular velocity and ($\tau$) is the torque. The power requirement for propulsion of the wheelchair is unchanged regardless of the wheel angular velocity, as the required propulsion power is a function of the forces and accelerations the MWC must overcome. Therefore to compensate for the low angular velocity ($\omega$) of a direct drive motor, the torque value ($\tau$) must increase to maintain the same power. This is done by increasing the diameter of the motor because the torque output of a BLDC motor is a function of the radial distance to the radial flux gap between the rotor and stator of the motor [76]. As a result of the larger diameter, direct drive motors can be heavier than a geared motor of equivalent power and torque output.

Direct drive motors do have several benefits. They are capable of regenerative braking. Direct drive motors are also gaining traction in precision robotics applications because they can provide optimized acceleration due to inertia matching, quieter operation due to the elimination of gearboxes, and no impact from gearbox backlash [77].

By contrast, a DC motor and gearbox take advantage of the gearbox's ability to increase the output torque and decrease the output speed while still maintaining a high power density. This means that a smaller, lighter BLDC motor that spins very fast (with a low torque output) can be coupled with a gearbox to meet the power output and velocity/torque requirements of the driven system and provide a lighter overall system than an equivalent direct drive motor. The downsides of geared BLDC motors include the frictional losses of the gearbox. Efficiencies of gearboxes as a result of frictional losses range anywhere from 49% to 98%, depending on the type of gearbox and number of reduction stages it contains [78]. In addition, geared BLDC motors can suffer from an increase in noise from the gearbox, and a potential inability to perform regenerative braking. Regenerative braking with a gearbox requires the gear system to be backdrivable, which means that the load can drive the motor through the gearbox. This is an issue for a MWC drive system as the user cannot push the wheel on a backdrivable geared system without turning the gearbox and motor, unless a clutch system to disengage the wheel from the gearbox and motor is introduced. Regenerative braking is a feature that could be of value in a PAW system, particularly for braking on a downhill slope, but was not implemented in this project.

Electric bicycle motors can provide some insight into the determining a drive layout, as they require a similar power output, angular velocity and output torque to wheelchair drive systems. Electric bicycle motors come in two configurations, hub motors and mid-drive motors. Mid-drive systems mount the motor in the frame and attach to the crank arm of the bicycle, taking advantage of the drivetrain's gear development for optimal power output. This allows a mid-drive motor to retain a relatively constant torque and angular velocity like the output of a human being. An example of a mid-drive motor system is shown in Figure 22.


**Figure 22: Bafang Mid-Drive Motor** [79]

Hub motors replace either the front or rear wheel of the bicycle and come in either geared of direct-drive versions as described previously. Geared hub motors can typically weight about 50% less than an equivalently powered direct drive machine in the electric bicycle industry [80]. All direct drive hub motors can perform regenerative braking, while most geared hub motors cannot. Hub motors are favored for their simplicity, lack of impact on drivetrain wear, and high peak power capability [81].

One innovative drive system in the bicycle industry addresses many of the project design requirements such as low mass and spatial design constraints. This system is the Vivax Electric Assist mid-drive, shown in Figure 23.

**Figure 23: Vivax Electric Assist System,** [82]

The Vivax Electric-Assist uses a small, high speed BLDC motor and a gearbox to power the crank arm spindle. This entire system is hidden inside the bicycle downtube and is not visible when in operation. The Vivax system can provide 200 Watts of electric-assist, and only weighs 1.8 kg including the battery [83]. This mass is extremely low, with smaller conventional electric-bicycle hub motors weighing at least 2.7 kg [80], meaning that with a battery a conventional e-bike drive system weighs over double the mass of the Vivax system.

Currently available PAWs use almost exclusively hub motors, similar in construction to electric bicycle hub motors, or in some cases relying directly on components from electric-bicycles. The Alber Twion, Alber E-Motion and Yamaha JWII PAPAWs are all direct-drive hub motors, a layout that is directly responsible for some of their identified limitations. Specifically, the high mass of these PAPAWs, the large diameter of the hub shell which does not allow for one-handed removal and installation and the increased wheelchair width are all consequences of the direct-drive motor topology in these PAPAWs. Based on these observations and the demonstrated functionality of lightweight geared systems such as the Vivax electric-assist, it was decided that the proposed system would incorporated a small BLDC motor and a high reduction gearbox to minimize system mass and provide a unique layout to address spatial usability design requirements.

### *Integrating a Geared Motor into a Power-Assist System*

The successful implementation of a geared motor in a power-assist system required concept development beyond the simple sub-categories described in the Work Breakdown Structure. For this reason, once it was determined that a BLDC motor and gearbox were to be used for the drive system, some creative brainstorming and engineering calculations had to be performed to determine a system layout that could satisfy as many design requirements as possible. This section will describe this process and how the eventual design was developed.

A motor system requires that the speed of the input motor can meet the speed and torque requirement of the output. For a BLDC motor operating in a power-assist system, this means that the drive motor must have a speed range to accommodate for the entire linear speed range of the wheelchair (e.g. 0-2.5 m/s). If the BLDC motor cannot meet the range of speed requirements, then a gearbox with changeable drive ratios can be employed (similar to the type of gearbox in an automobile manual transmission), but this adds cost, mass and complexity. The solution is therefore to source a BLDC motor and gearbox combination that match the range of speed and torque requirements of the system design requirements.

Another limitation on the selection of the motor and gearbox layout included the actual physical design space of the wheelchair frame. Specifically, the design requirements concerning wheelchair width, maintaining a conventional wheelchair axle and fitting a variety of manual wheelchairs. For example, a solution might be to install the BLDC motor and a planetary gearbox inside the hub shell of the wheelchair wheel, similar to geared hub motors for bicycles. This design is simple to implement, but does not meet design requirement 2.06, where the wheel must be removable with one hand. An in-hub system also has the potential to increase the wheelchair width, similar to how the Twion system increases the overall width.

To help describe the following concepts in this section, an overview of gearboxes and gear system types is included in Appendix A.

From a high level perspective, the simplest layout for a geared drive system therefore appeared to be one where the motor and gearbox are concentric with the wheelchair hub, (Figure 24.

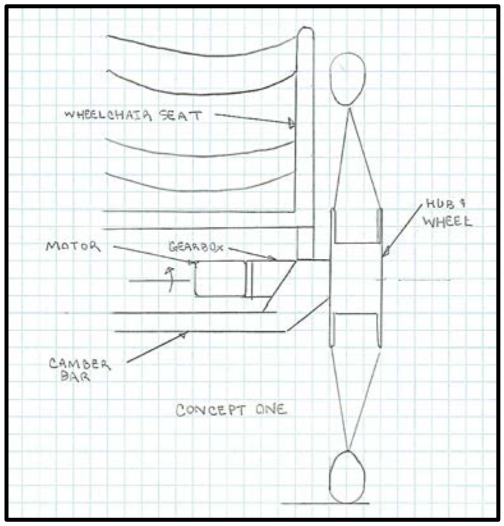


**Figure 24: Concept One Drivetrain System, Source: Own Work**

This concept has numerous advantages. The concentricity of all shafts makes for easy manufacturing and assembly. The concept does not require any of the more complex gear tooth shapes such as bevel or worm gears, instead relying on a compact multi-stage planetary gearbox for the necessary reduction.

Despite these advantages, the concept cannot meet all design requirements. Specifically, the concept requires a unique integrated wheelchair design, cannot accommodate different wheelchair widths (design requirement 1.03) and completely interferes with the ability to use a conventional wheelchair axle (design requirement 3.05) as well as the ability to accommodate wheelchair configurations with large seat “dump,” where the user’s hips are situated below their knee when seated.

Concept two (Figure 25) attempts to address this problem by incorporating a large reduction gear at the final gear stage. This allows for the output shaft of the wheelchair hub and the gearbox/motor shaft to be non-concentric, but parallel.

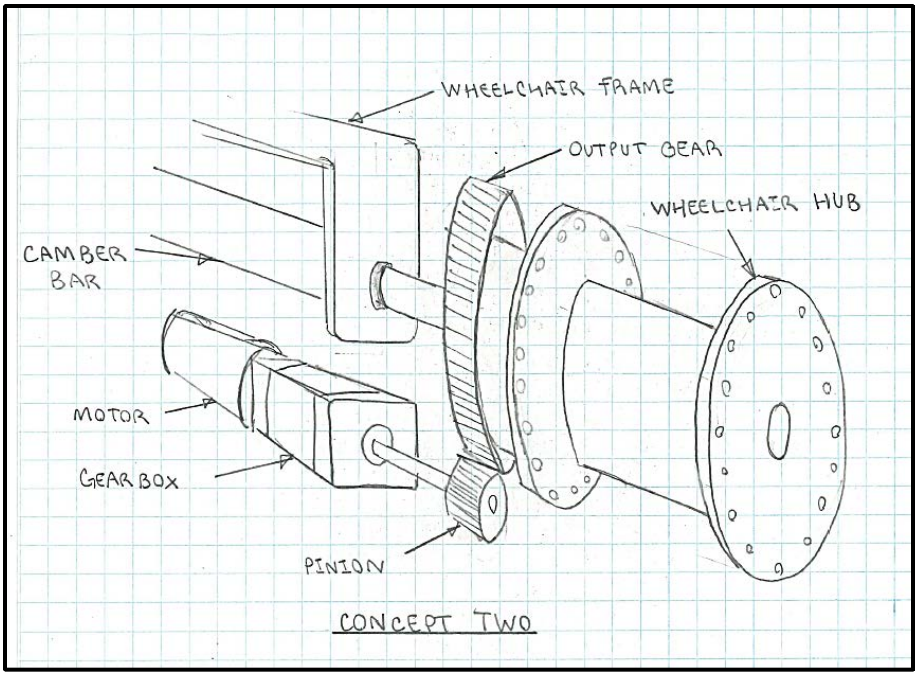


**Figure 25: Concept Two Drivetrain System, Source: Own Work**

This concept does well to satisfy many of the design requirements. Theoretically the system could fit a variety of wheelchair designs, as the space underneath an ultralight manual wheelchair where the motor could sit is unoccupied and protected by the frame and wheels of the chair. Detailed design of this concept could also allow for the use of a conventional wheelchair axle (requirement 3.05), as well as wheelchair wheel hubs that are of a diameter that can be easily handled for removal and installation. The use of a conventional diameter wheelchair hub also allows for the ability to select a rim diameter during assembly (requirement 3.03) as well as the use of a pneumatic tire. Concept two can also be driven in forward or reverse to satisfy design requirement 3.01.

However, there are several drawbacks to this concept. The width of the wheelchair is a major design constraint, as an ultralight manual wheelchair frame is usually designed to optimize the fit of the wheelchair user by minimizing the frame width. This places the wheels as close as possible to the user and can help to decrease shoulder abduction during propulsion [84] as well as provide clearance for navigating tight spaces such as door thresholds [27]. This concept is impacted in two ways by the wheelchair width. Firstly, the output gear between the wheelchair hub and the wheelchair frame will almost certainly increase the overall wheelchair width because of the additional space required for the gear. Secondly, the axial length of the motor and gearbox combination is constrained by the overall wheelchair width. The motor/gearbox cannot be longer than half of the wheelchair width provided the system is symmetrical, or the left wheel system will interfere with the right wheel system.

In addition to the width constraints, the use of a single spur gear pinion could place large amounts of stress on this gear. The output gear must be of a large enough diameter to clear the wheelchair frame area at the rear axle. The pinion diameter is ideally minimized for a large reduction ratio, but too small of a pinon will place undue wear on this gear. Although the functional layout of the concept appeared like a good solution for the design requirements, further development was needed to address these drawbacks.

Research into existing system that combine a gear reduction with a driven rotary output provided insights to drive design concept three. Looking at available power tools provided some ideas of how to incorporate brushless motors and gear reduction. A cordless drill is like concept one, where the drive system is concentric with the output. However, other power tools such as the angle grinder make use of a spiral bevel gear to reduce the motor speed and change the axis of rotation of the motor. An angle grinder is shown in Figure 26.


**Figure 26: Angle Grinder, Licensed under CC BY-SA, Author: Team Metabo OS** [85]

A spiral bevel gear has also been employed in a similar configuration to the spur gear in concept two in the Christini All Wheel Drive (AWD) mountain bike. The Christini AWD makes use of a spiral bevel gear and pinion at the dropout of the rear wheel of a mountain bike to transmit power to the front wheel. A picture of the patent is shown in Figure 27.

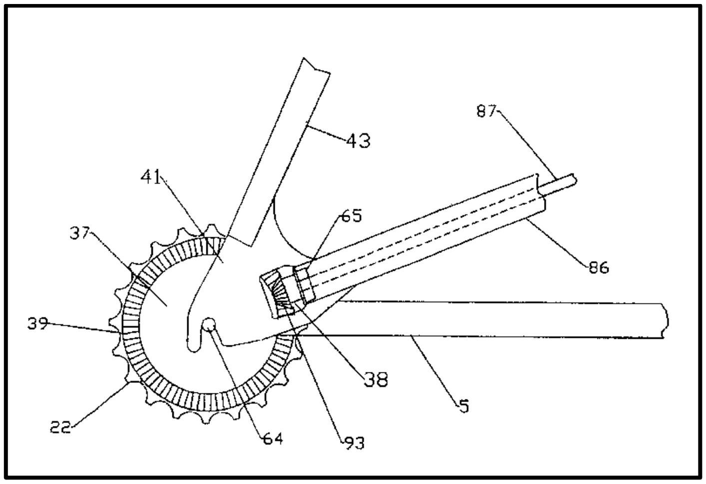


**Figure 27: Christini AWD Spiral Bevel Gear** [86]

The Christini AWD drive system provided credibility to the concept of a spiral bevel gear as the drivetrain component between the wheelchair hub and the drive motor. This would allow the theoretical system to be positioned either below or behind the wheelchair frame, with the motor oriented radially to the wheel, much like component 86 in Figure 27. This orientation eliminates the width constraint of concept two. The spiral bevel gear has the additional benefit of being quieter and smoother than spur gears [87].

Worm gear sets are also used in power tools and other similar applications where a drivetrain is coupled to a BLDC motor and requires reorientation of the output axis. Therefore, a worm gear set could be considered ideal to address the previously stated design constraints. However, the fact that worm gear sets are often non-backdrivable means that the system could never be in a state where the output wheel drives the motor. Backdriving occurs in power-assist systems during coasting or when performing regenerative braking. In addition, the large velocity ratios of a worm gear set were estimated to not be needed for a power-assist system.

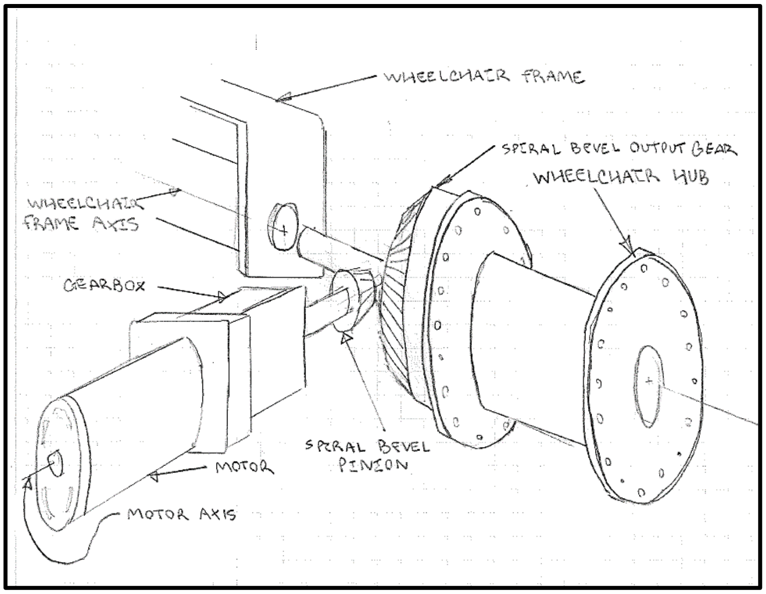


**Figure 28: Concept Three Drivetrain System, Source: Own Work**

Concept three is shown in Figure 28. The layout is similar to concept one and two but with the addition of a spiral bevel gear to change the axis of rotation and orient the motor to the rear of the wheelchair. Similar to concept two, this concept could also allow for the use of a conventional wheelchair axle (requirement 3.05), as well as removable wheelchair wheel hubs (requirement 3.06). The use of a conventional diameter wheelchair hub allows for a pneumatic tire (requirement 3.03).

The shape of a spiral bevel gear upon initial analysis appears to be designed for driving in one direction only. However, spiral bevel gears are regularly used in automobile transmissions where they are driven in reverse [88]. The convex output gear side rolls with the concave pinion flank as the dominant direction, with this side being termed the “drive side” of the gear set. The reverse direction is referred to as the “coast side” but can be used to drive the system, with some loss of efficiency [89]. Based on this research the spiral bevel gear is a suitable choice to satisfy the forward/reverse design requirement 3.01. The spiral bevel gear is also more efficient, quieter running, and capable of higher reduction ratios than a spur gear reduction [88].

Based on these researched benefits and the unique layout potential of spiral bevel gears, it was decided that the spiral bevel gear concept presented the best opportunity for further exploration and design development.

### *Integrating the Wheelchair Wheel into the Conceptual Drivetrain*

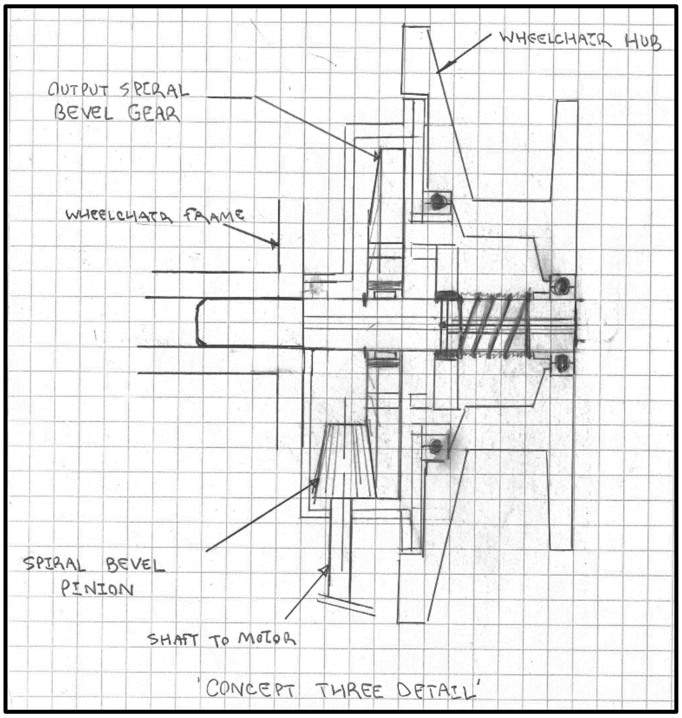


**Figure 29: Concept Three Detail, Source: Own Work**

Figure 29 shows a detailed layout for concept three. This layout helped to identify an important challenge with this design; the bevel gear pinion must occupy space between the wheelchair frame and the inner hub flange of the wheelchair hub. This is a problem because it potentially increases the width of the wheelchair system if the distance between the hub flanges of the wheelchair hub remains the same as a conventional wheelchair wheel.

This problem is not unique to power-assist systems and is a problem in the design of bicycle rear wheels. For a spoked wheel of the type on bicycle or wheelchairs, the spokes must maintain sufficient bracing angle to balance the axial and radial tension and keep the rim in true. The bracing angle is the angle between the spoke and the axis of rotation of the wheel. If the bracing angle was 90°, the spokes would be vertical and not able to resist and axial forces on the rim. To provide sufficient bracing angle, hub designers try to maximize the distance between hub flanges. In addition, a larger hub flange diameter can create a better bracing angle, but will add weight in the form of increased material at the hub flange. The ideal hub flange geometry has maximum distance, evenly spaced flanges from the hub centerline with a minimal flange diameter.

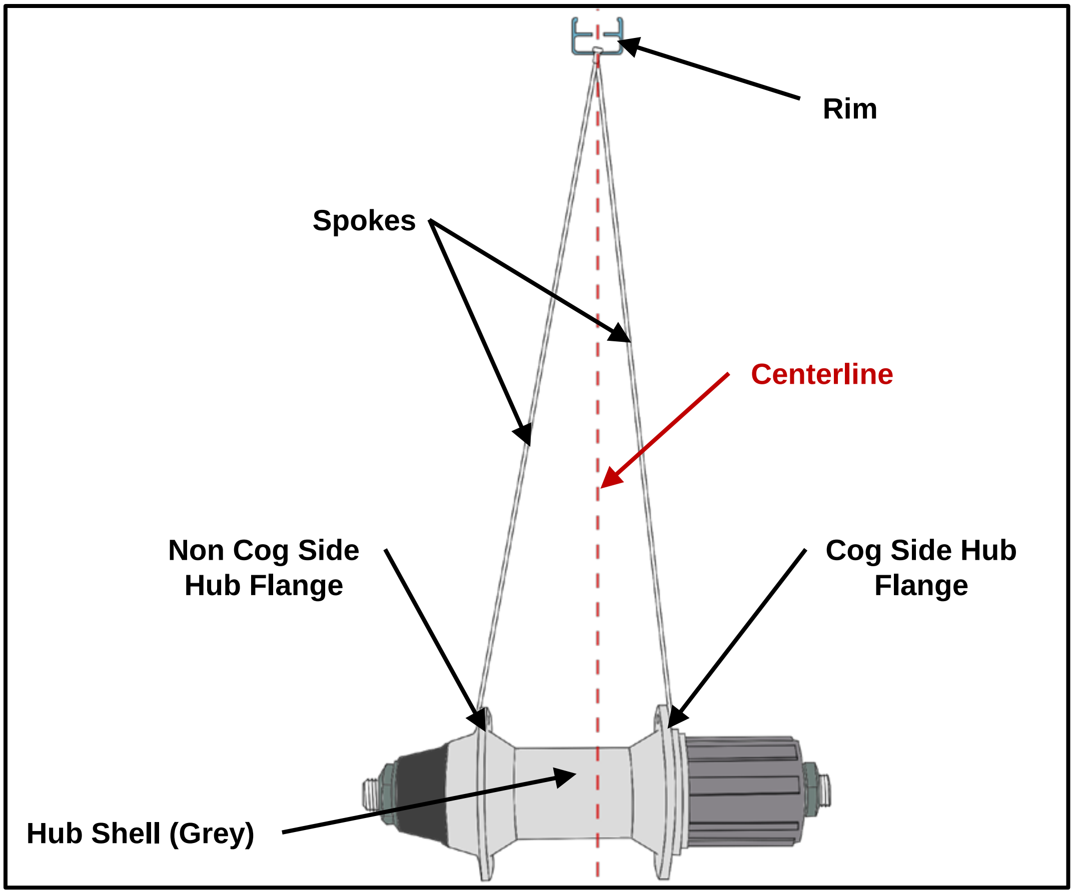


**Figure 30: Bicycle Hub Dish, Licensed under CC BY-SA, Author: Keithonearth** [90]

The problem is that for a bicycle to have gears it must have rear cogs which occupy space along the axial length of the rear hub. This means that the hub flanges would be too narrowly spaced if they were placed symmetrical about the hub centerline. The solution is to space the cog-side flange of the bicycle closer to the centerline of the hub, and to use shorter spokes on the cog-side flange. An example of this is shown in Figure 30, where the right hand cog side flange is slower to the red hub centerline. The offset of the rim relative to the hub centerline is termed "dish." The wheel pictured in Figure 30 is dished to the center of the hub, with the right hand hub flange being closer to the centerline and shorter spokes being used to allow for proper dish and spoke tension. The bracing angle is less on the right hand spokes, but the axial tension can still be balanced based on the spoke placement. Some hubs will also use different cog-side and non-cog-side hub flange diameters to create a better cog-side bracing angle.

This is important for the design of a wheelchair power-assist system because we are seeking to (1) not increase the wheelchair hub width and (2) maintain the position of the rim relative to the wheelchair frame. Placing a spiral bevel gear assembly in between the wheelchair frame and the wheelchair hub as in Figure 29 using a hub with standard flange dimensions would increase the wheelchair width. The conceptual solution is therefore to space the hub flanges of the wheelchair hub closer together to accommodate for the space occupied by the spiral bevel gear and to offset the rim dish to match the centerline of a traditional wheelchair wheel. This makes it so that the rim is the same distance relative to the wheelchair frame to maintain the same biomechanical position for the power-assist system as an unpowered wheel.

### *Selecting a Motor and Gear Reduction Ratios*

Once a general layout and concept was established, a suitable motor and gearbox had to be chosen. Primary drivers in the design choices for this section included cost, ease of prototyping, and availability of parts. The first design challenge came in finding a suitable spiral bevel gear.

The majority of available right angle gear sets from industrial sources such as McMaster Carr or Rush Gears were either too physically large for the design size contained in heavy and complex gear housings not suitable for meeting lightweight design requirements. In addition, the cost for these gear sets was prohibitively expensive for an initial prototype, with typical suitable gearboxes costing approximately $500.00 CAD (Ondrives.Us, Shaft to Shaft Bevel & Bevel-T Gearboxes). Therefore, an inexpensive spiral bevel gear was sought.

A source of affordable spiral bevel gears with radius and geometry similar to fit into the design space of the wheelchair wheel and frame included the gears found in angle grinders. With angle grinders priced as low as $14.99 CAD [91], purchasing an angle grinder to use the gears represented a significantly lower cost to prototype and test the spiral bevel gear concept compared to a custom gear. Unfortunately, purchasing off the shelf angle grinder meant not being able to specify the precise gear geometry. However, robot hobbyists have successfully adapted angle grinder spiral bevel gears for projects [92], which provided support for this approach. An example of a spiral bevel gear contained in an angle grinder is shown in Figure 31.

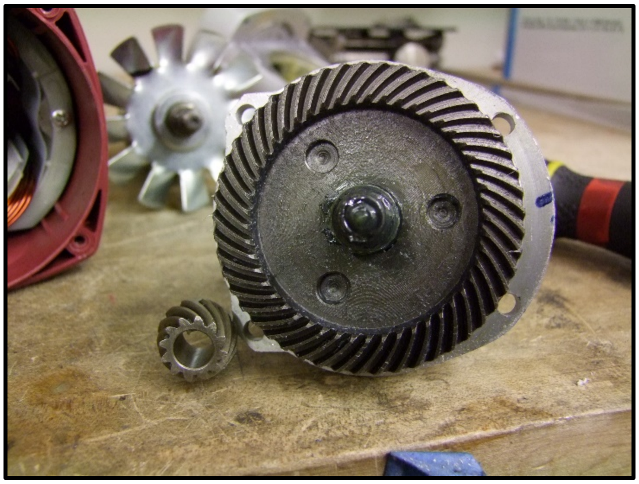

**Figure 31: Angle Grinder Bevel Gear, Licensed under CC BY-SA, Author: Charles Z. Guan** [92]

An angle grinder was purchased for the purpose of using the gears. The one selected was designed for a 9” cutting disc, with the assumption that a larger disc would require a larger reduction gear. The spiral bevel gear and pinion were made of steel, with a tooth count of 9 for the pinion and 37 for the output gear. This resulted in a velocity ratio of 4.11111, which is a “hunting tooth” combination that eliminates repetitive wear on the gear teeth by using a fractional velocity ratio.

With the ratio of the spiral bevel gear fixed, a motor and gearbox were selected. This combination was required to meet the complete speed and torque range of the output. BLDC motor technology has undergone considerable development over the past three years, with the remote control device market (e.g. quadcopters and planes) being responsible for the ubiquity of cheap, powerful BLDC motors. These motors are well suited to prototyping a power-assist system, as they are inexpensive, modifiable and robust enough to be tested. The primary drawbacks of BLDC motors optimized for BLDC motor manufacturers provide a series of specifications for determining which motor is suitable for an application.

Specifications given by motor manufacturers for determining the suitability of a BLDC motor for a PAW application include the motor constant $K_v$, the maximum power and amperage, a maximum operating voltage and a mechanical top speed.

The motor velocity constant $K_v$ is the ratio of the motor's unloaded rpm to the peak voltage. If the $K_v$ constant of the motor is multiplied by the theoretical input voltage, the designer can get an idea of the maximum output speed of the motor. For a theoretical BLDC motor, the peak power is achieved at half the no-load speed. Therefore, the system designer can use the motor velocity constant $K_v$ as a rough guide to gain an understanding of a motor's suitability for an application. Torque and speed graphs are further used to confirm a system's suitability.

Another valuable motor constant is the torque constant $K_t$. This gives a picture of the amount of torque output by the motor depending on the input current. If the torque constant $K_t$ is in N-m/A and the velocity constant $K_v$ is in rad/s per volt, then,

**6**

$$K_t = \frac{1}{K_v}$$

If the required output torque is known, the motor constant $K_t$ can be used to calculate the input current for that torque load. These two motor constants can be used to compare different motors and determine their suitability for the application.

To determine the correct motor and gearbox for the system, a trial and error process was employed based on the motor specifications and the design requirements for torque and speed. A simple model of the system is shown in Figure 32.

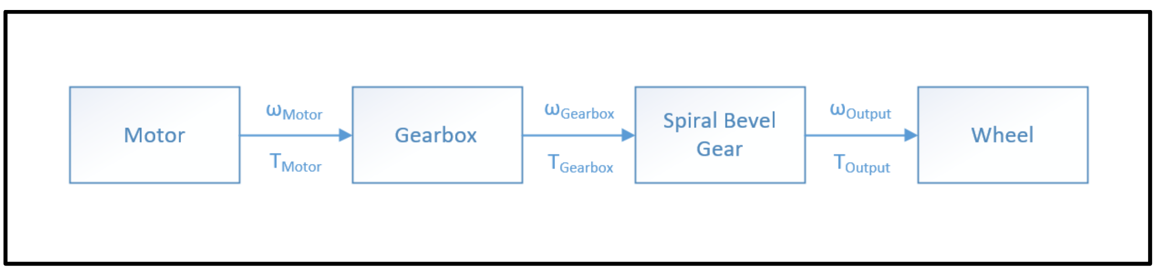


**Figure 32: Simple Model of Power for System, Source: Own Work**

The wheel and the spiral bevel gear are directly mechanically coupled, and therefore share the same torque and angular velocity. The reduction ratio of the spiral bevel gear was fixed by the chosen gear set from the angle grinder. This gave a known value of torque and angular velocity to be met from the gearbox and motor combination.

The torque and angular velocity requirement at the output shaft of the gearbox is shown in Table 11.

**Table 11: Torque and Angular Velocity Requirements**

| | Output Wheel | Gearbox Output Shaft |
|---|---|---|
| Continuous Torque Output (Nm) | 20.8 | 5.07 |
| Peak Angular Velocity (RPM) | 78.3 | 321 |

The selection of a motor and gearbox combination represented a difficult problem to overcome, simply because of the sheer volume of available motors, gearboxes and drive components. For this reason, it was decided for the initial prototype to use motors and gearboxes that had been previously used in the lab, so that prior experience with construction, quality and functionality of the motors and gearboxes could be utilized.

The selected gearbox manufacturer was BaneBots, as they provide a series of inexpensive gearboxes with a range of reduction ratios. Specifically, the BaneBots P60 gearbox is available in 4:1, 16:1, 20:1, 26:1 and 64:1 reductions, with prices ranging from $50.00 CAD to $80.00 CAD. Several potential motors with low motor velocity constant $K_v$ were available in the lab supply and were investigated as potential candidates. The investigated motors are listed in Table 12:

**Table 12: List of Potential Motors**

| Motor Name | KV rating (RPM/volt) | Cost (CAD) |
|---|---|---|
| Turnigy Aerodrive SK3-192KV | 192 | $125.00 |
| Turnigy Aerodrive SK3-280KV | 280 | $75.00 |
| Turnigy Aerodrive SK3-430KV | 430 | $75.00 |
| Turnigy Multistar 6340-230 KV | 230 | $120.00 |
| Scorpion HKIV-5035-380KV | 380 | $500.00 |
| Scorpion HKIV-4035-520KV | 520 | $350.00 |

A motor and gearbox combination were selected using the approach described in the following steps:

1. Select a gearbox reduction ratio from the available options.
2. Confirm that specified maximum gearbox output torque can safely handle the required torque load.
3. Calculate the peak angular velocity of the motor output shaft based on the gearbox reduction ratio.
4. Check the maximum electrical speed of a potential motor based on the motor velocity constant $K_v$ and a 36 Volt output (requirement 2.07). Use as guideline for upper bound of motor's speed capability.
5. Check the current requirement based on the required continuous output torque and the motor torque constant $K_t$.

Based on a 16:1 gearbox reduction ratio, the torque and angular velocity at the motor output are summarized in Table 13.

**Table 13: Motor Output Requirements**

| | Gearbox Output Shaft | Motor Output Shaft |
|---|---|---|
| Continuous Torque Output (Nm) | 5.07 | 0.317 |
| Peak Angular Velocity (RPM) | 322 | 5150 |

The quoted peak maximum torque for a BaneBots P60 gearbox output shaft is 61 Nm. This is the value through the company's bench testing where the device fails. No further failure or fatigue data is given by the company. Based on this maximum torque, the BaneBots 16:1 P60 gearbox is well within specification for the calculated RMS and peak torque reflected to the gearbox output. The gearbox does not specify any maximum angular velocity for input or output, but the manufacturers confirm that the Banebots P60 gearbox can be coupled with DC motors with speeds up to 18000 RPM

Given the spiral gear reduction of 4.11:1 and a gearbox reduction of 16:1 the required peak angular velocity at the motor output shaft to propel the wheelchair at 9 km/hr is 5150 RPM. The Turnigy Aerodrive SK3-280KV BLDC outrunner motor does not have a specified maximum angular velocity, but we can calculate the no-load angular speed of the motor using the motor velocity constant $K_v$ and use this as an approximate maximum angular velocity of the motor. Based on the motor velocity constant (*$K_v$=280 RPM/volt)*, the no load speed was calculated using Equation 7 to be.

**7** $$36\,Volts \times \frac{280\,RPM}{Volt} = 10{,}080\,RPM$$

This non load speed indicated that the required speed of the motor to propel the wheelchair at 9 km/hr is within the attainable range of the selected motor. The current draw of the motor during continuous output torque was then calculated, based on the motor torque constant $K_t$.

**8** $$\frac{1\,Amps}{0.0341\,Nm} \times 0.317\,Nm = 9.296\,Amps$$

This value for current draw means that the system will need a ~10 Amp-Hour battery to run for one hour in the continuous torque ramp driving condition. The current draw during flat ground driving will be 2.786 Amps, based on the previously calculated torque estimates. These values of current are acceptable for the types of current output from 36 Volt lithium-ion ebike batteries, which can range in size from 2.7 Amp-Hours to 27 Amp-Hours [93]. If the current from this calculation were too high, then the calculation needs to be redone with either a different motor or gearbox combination. Completing these calculations indicated that the motor and gearbox combination would satisfy all initial design goals, and the project was able to move into the detailed design phase.

## 3.3. The NeuwDrive System

After a motor and drive system layout had been selected, a simple physical system layout was constructed in the 3D modeling software SolidWorks. Initial modeling began by laying out the drive system for concept three, and then modeling the surrounding components to make the system compatible with the remaining design requirements. The computer model passed through over 20 major iterations before settling on a design that was ready for fabrication. Several different prototype iterations are shown in Figure 33

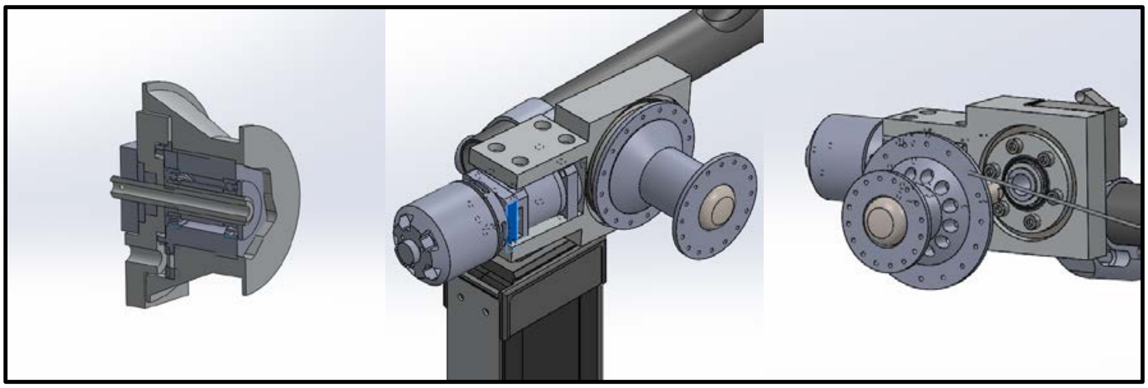

**Figure 33: Prototype Iterations, Source: Own Work**

Upon completion of the 3D model, a series of manufacturing drawings were created, material was procured, and fabrication of the prototype was started. The first prototype included nine major components that had to be made using a variety of process including manual and Computer Numerical Control (CNC) machining, 3D printing, and waterjet cutting. After completion of all fabrication, the prototype components were assembled. The prototype assembly included 55 unique parts. The complete assembly is shown on the following page in Figure 34.

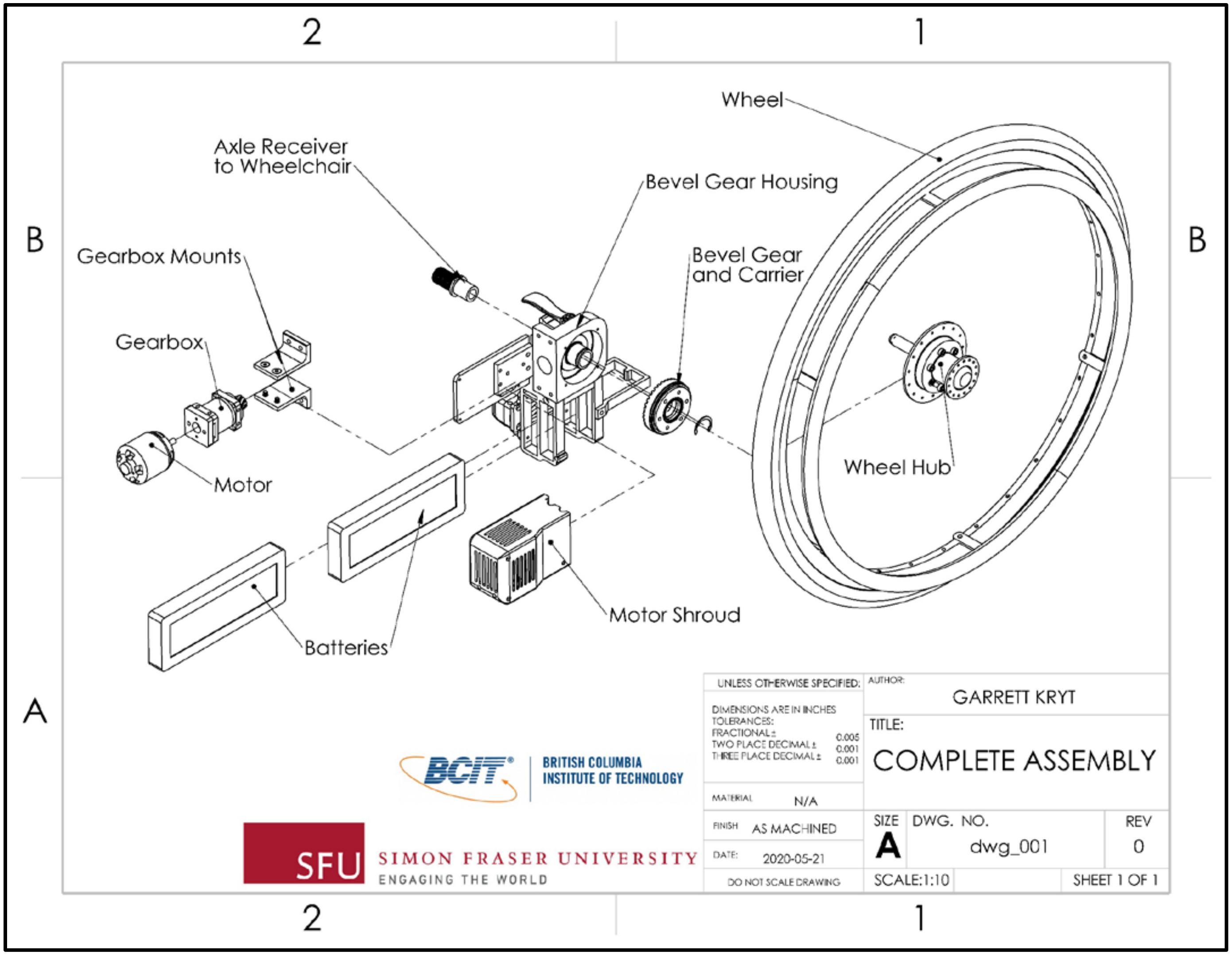


**Figure 34: Exploded Assembly, Source: Own Work**

During fabrication, the prototype was named NeuwDrive, for “Novel Electric Universal Wheelchair Drive.” This name stuck with the prototype throughout the project, and the system will be termed NeuwDrive for the rest of this document. The NeuwDrive is shown in Figure 35 and Figure 36.

**Figure 35: The NeuwDrive System, Source: Own Work**

**Figure 36: Closeup of NeuwDrive System, Source: Own Work**

The following section will provide details of the design and fabrication of the components of the NeuwDrive system.

### 3.3.1. Battery System

Figure 37 shows the selected batteries and layout in the system. The batteries for the prototype were 36 Volt LiGo batteries from Grin Technologies (Vancouver, British Columbia). These prefabricated batteries were made up of ten LG MG1 18650 Lithium Ion cells and come encased in plastic with a built-in battery management system circuit and color-coded lead wires. A single ten cell battery was capable of 10 Amps continuous current, 15 Amps peak current, and had a 98 Watt-hour capacity. Based on these specifications, two LiGo batteries stacked in parallel were expected to provide 32 minutes of continuous torque testing for the prototype. Since the continuous torque provides some overhead in the calculation, this battery capacity was determined to be suitable for preliminary testing.

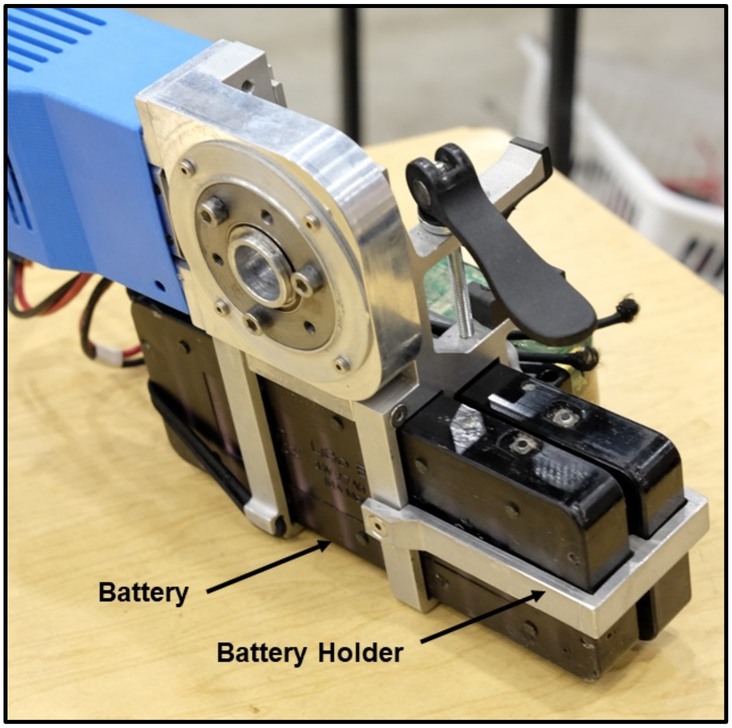


**Figure 37: System Batteries, Source: Own Work**

The LiGo batteries had the additional benefit of having a form factor that lent itself to fulfilling design requirement 3.02, which stipulated that the batteries must be easily removed and installed. The battery holder was designed so that the batteries could slide in and out with ease, and were retained using an elastic strap. This demonstrated the functionality of a user being able to install one battery to decrease the system mass, or two batteries to increase the system range.

### 3.3.2. Drive System and Gear Housing

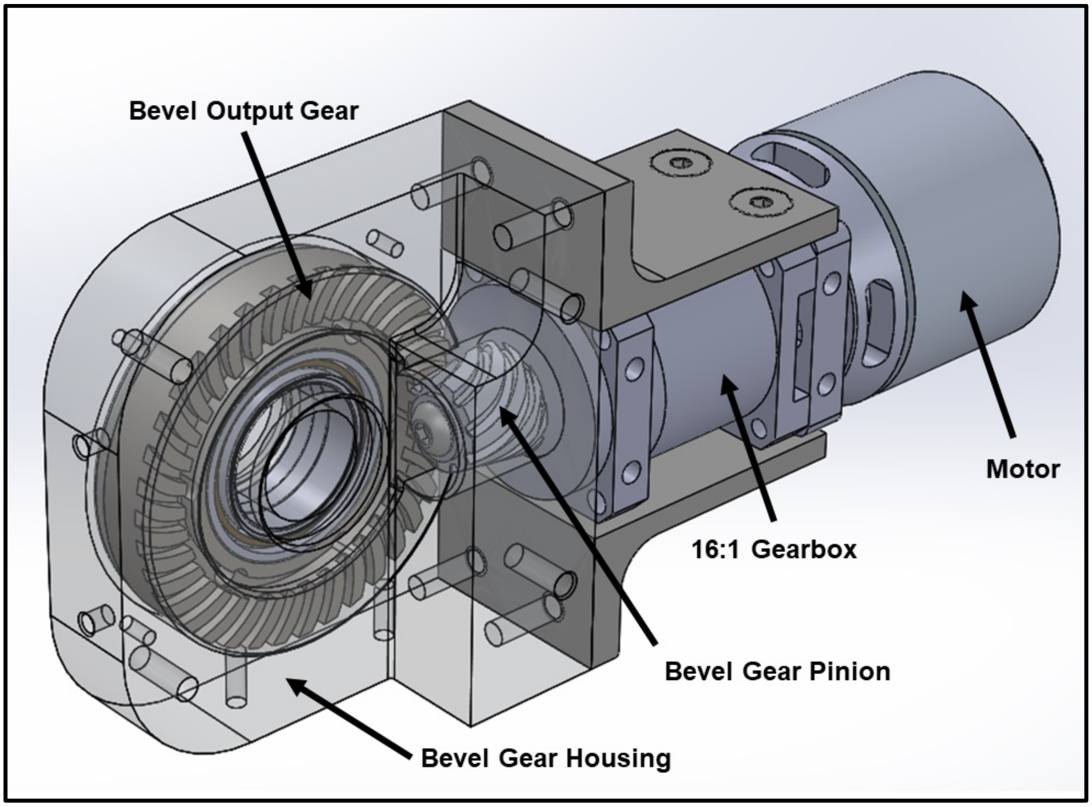


**Figure 38: Drive System Layout, Source: Own Work**

Figure 38 shows the layout of the gear drive system. This drive system layout required careful reverse-engineering of the angle grinder gear housing to determine the correct position of the bevel output gear and pinion. The gearbox shaft was machined to accept the bevel gear pinion, and the motor and gearbox required a custom adapter plate to be mounted together.

The gearbox housing was the most complex part of the entire system to fabricate, requiring several CNC machining processes. The spiral bevel output gear is attached to a carrier, which rests on two bearings that allow for the carrier to rotate relative to the gear housing. This layout required a specified fit for the inner bearing races as well as a thin retaining ring groove to locate the bevel output gear carrier inside the gear housing. The spiral bevel gear system is lubricated with a molybdenum grease which is retained using a ring seal and cover plate on the outside of the gear housing.

System Installation

The majority of ultralight wheelchair designs fall into two categories of frame design. The open frame design is shown in Figure 39 and consists of two main frame tubes with a single tube extending to the rear axle. The closed or box frame design is shown in Figure 40 and is made up of two smaller tubes that extend to the rear of the chair to add rigidity. The rear axle is generally located between these tubes and attaches to a bracket.

**Figure 39: Open Frame Wheelchair, Reproduced according to terms and conditions of Sunrise Medical** [94]

**Figure 40: Closed Frame Wheelchair, Reproduced according to terms and conditions of Sunrise Medical** [94]

The component that both of these designs have in common is a round tube that is located near the rear axle of the wheelchair, either relatively horizontally or vertically. With design requirement 1.03 stating that the system must fit a variety of MWC designs, it was determined that coming up with a system that clamped onto a round tube near the axle to provide a counter-torque attachment could be a modular solution. The system would then have a different clamping bracket that would match a user's wheelchair. This is similar in principle to the brackets of the Twion and SmartDrive systems, which are specific to the frame design. The SmartDrive and Twion systems also require a permanently mounted bracket on the MWC frame. In the case of the NeuwDrive however, the bracket would be completely removable with the system, leaving no bracket on the MWC.

The attachment mechanism is shown in Figure 41. The two jaws clamp the rear tube using a clearance-fit, which is then fully clamped onto the tube using a quick-release cam handle. The two jaws are made from aluminum and use Delrin inserts to not scuff the tube and provide some compression upon clamping.

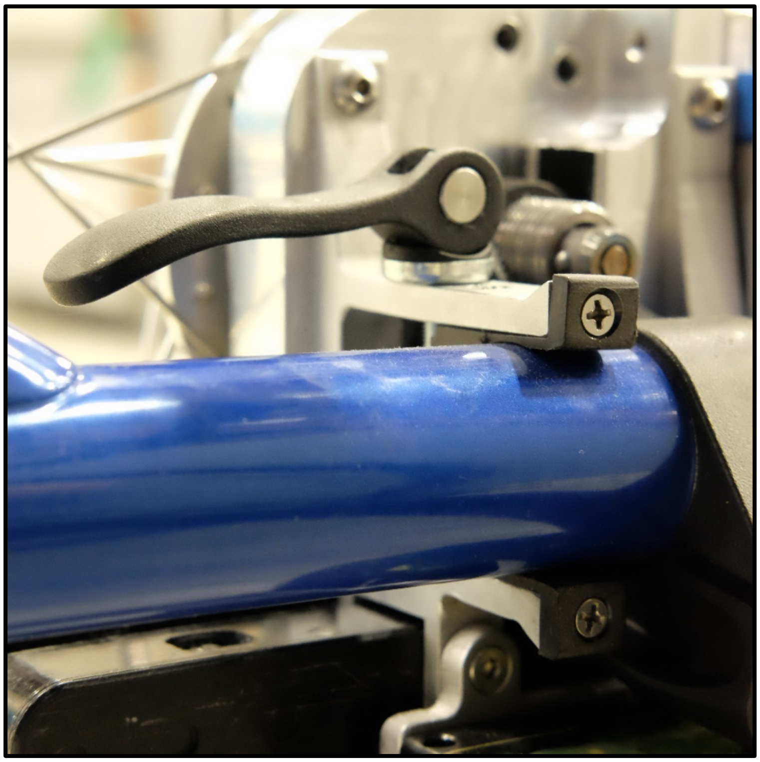

**Figure 41: Counter-Torque Mechanism, Source: Own Work**

This solution demonstrates the functionality of a clamping bracket system that could be implemented for different wheelchairs based on their specific tube shape and orientation. The clamping jaws also allow for easy removal and attachment of the NeuwDrive system, requiring only a light effort to install on the wheelchair. The system can be removed with one hand during car transfers, in keeping with requirement 3.06.

### 3.3.3. Wheelchair Width Solution

Figure 35 shows the NeuwDrive system protruding from the wheelchair, which would be expected to increase the overall wheelchair width. However, through a unique hub and axle design, the NeuwDrive system does not increase the overall wheelchair width and also maintains a conventional wheelchair axle. This section will discuss the resulting component design.

The wheel is removable in the same way as a conventional wheelchair wheel, and makes use of a splined interface to mate the wheel hub shell with the gear carrier. A splined interface is a system for coupling concentric objects to allow torque transfer. Splines can have different shapes depending on the design requirements. A male and female shaft spline system is shown in Figure 42.

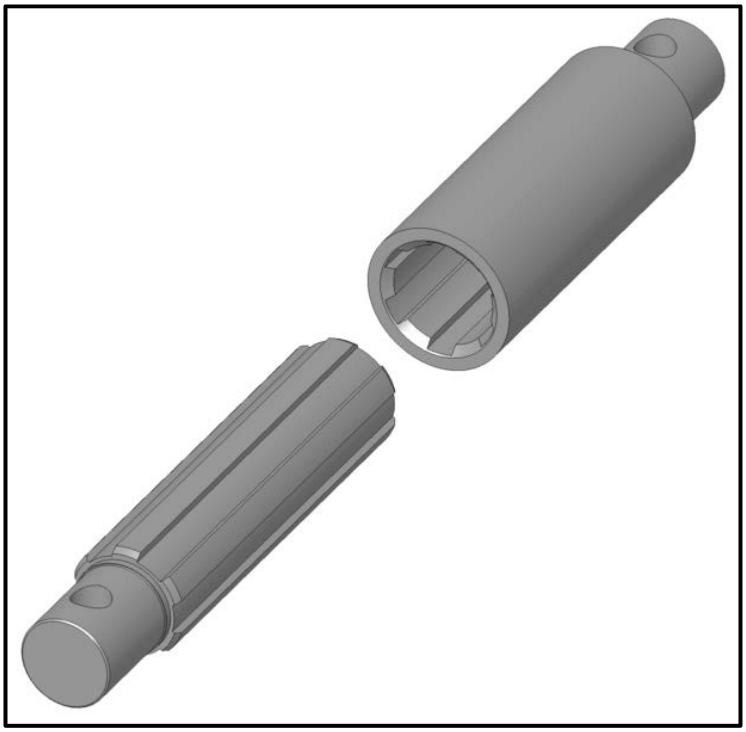

**Figure 42: Spline Interface, Licensed under CC-BY-SA-2.5, Author: Silberwolf** [95]

The splined system for the NeuwDrive was prototyped using M6 bolt heads for torque transfer. The splined interfaces are shown in Figure 43 and Figure 44.


**Figure 43: Gear Housing Splined Interface, Source: Own Work**

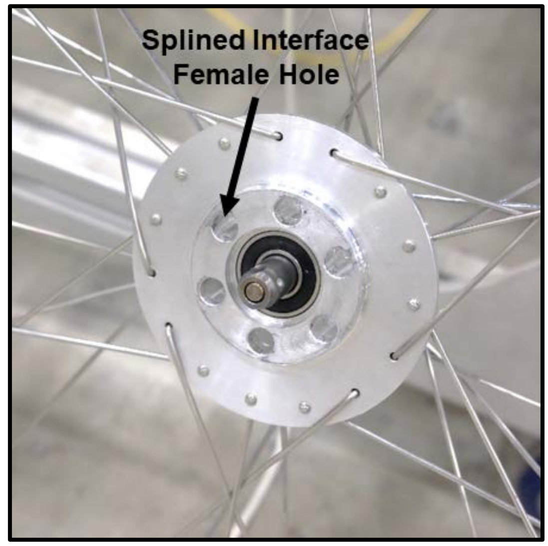


**Figure 44: Hub Shell Splined Interface, Source: Own Work**

This solution allowed for torque transfer between the two components, but the hub shell had to be engineered to not increase the wheelchair width and allow for the radial space that the splined interface occupies. The solution was to create a custom hub shell with one large flange and one small flange, with the rim dished axially towards the wheelchair frame. This maintains the rim position of the wheel relative to the wheelchair user, and does not increase the overall width of the wheelchair.

The next part of not increasing the wheelchair width while having the drive system positioned between the frame and the wheel was to design an axle receiver that could accept the conventional wheelchair axle, position the wheel at the correct position axially, and provide some rigidity to the gear housing.

The gear housing is made entirely from aluminum, the axle receiver was made from alloy steel to provide rigidity to the axle system and correctly position the gear housing. This also means that the axle receiver protrudes at a distance equal to the axial length of the gear housing from the wheelchair edge. This is longer than a conventional wheelchair axle receiver but has no impact on function.

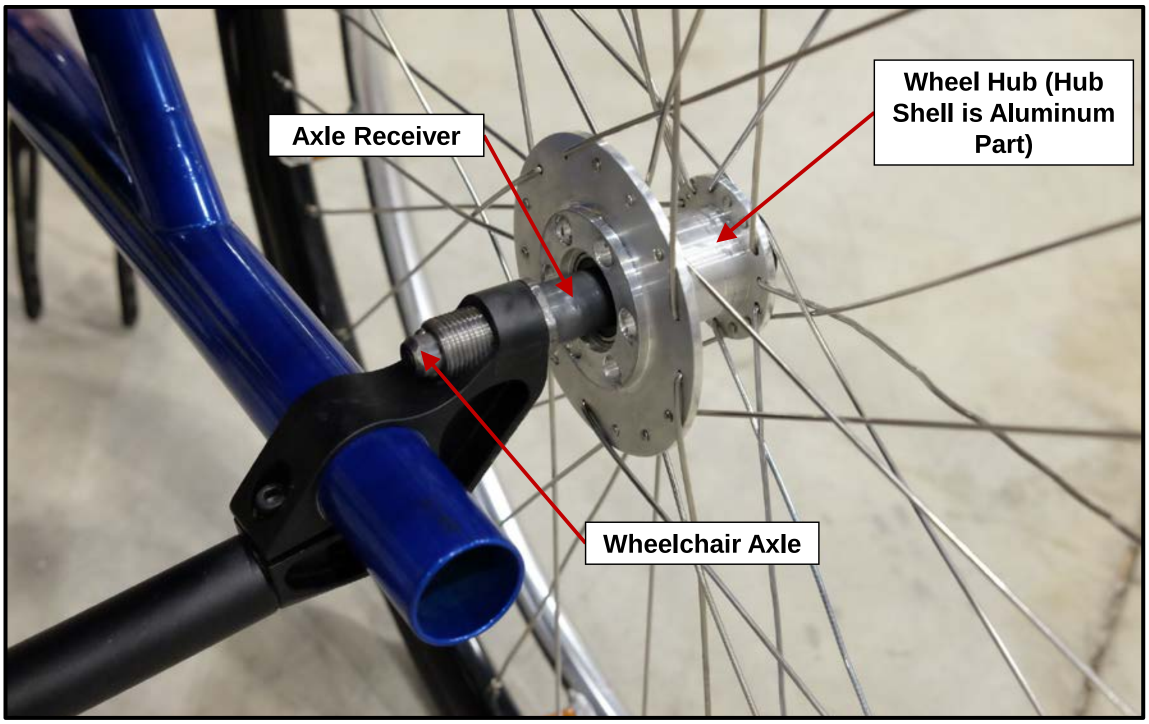


**Figure 45: Axle Receiver and Wheel Hub, Source: Own Work**

The wheel hub and axle receiver are shown in Figure 45. The inner bearing of the hub shell rests against the shoulder of the axle receiver in the same way as in a standard wheelchair hub. What this means is that when the drive system is removed from the wheelchair, the hub and rim are in the same position as when the drive system is installed. This maintains the biomechanical position of the wheelchair pushrim relative to the user. The additional benefit is that the MWC user can use the same wheel for the drive system and for manual pushing. This is an improvement over the Twion which requires the user to have a separate set of manual wheels. The aluminum hub shell and alloy steel axle receiver were custom machined using the manual lathe at the BCIT Applied Research fabrication facility. The hub shell is the same diameter as a conventional wheelchair wheel, and can be removed with one hand with the same ease as a standard MWC wheel in keeping with requirement 2.06, and uses conventional R8 sealed ball bearings and a standard half-inch steel wheelchair axle (requirement 2.05). The hub is built into a standard 25” wheelchair rim which could be changed for a different size (requirement 2.03) and uses a pneumatic tire (requirement 2.04).

### 3.3.4. Motor Shroud and Sensor

The Turnigy motor is an outrunner BLDC motor, and the rotor is therefore spinning freely on the outside of the motor. This presents a hazard to the user as the user could get injured from the spinning or get burned by the heat output. To protect the user from the motor and to lend a finished look to the prototype, a motor shroud was designed to cover the motor and gearbox.

The motor shroud required several iterations because of the tight tolerances between the hub shell, wheel spokes and shroud. The shroud was 3D printed from (Acrylonitrile Butadiene Styrene) ABS plastic. Using 3D printing in this instance allowed for quick analysis and changes to a design and allowed for part complexity that would not have been possible using other processes. The system is shown with and without the motor shroud in Figure 46 and Figure 47.

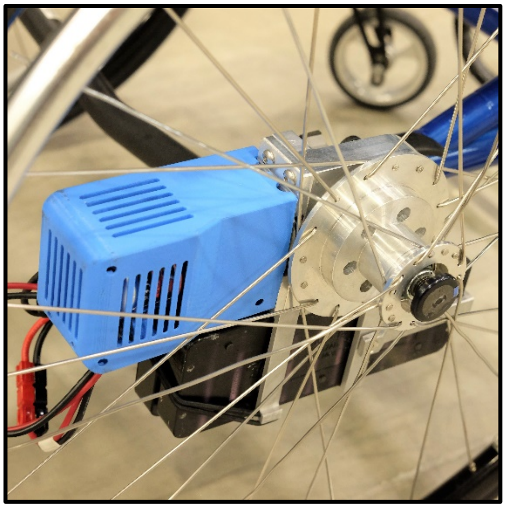

**Figure 46: Motor Shroud, Source: Own Work**

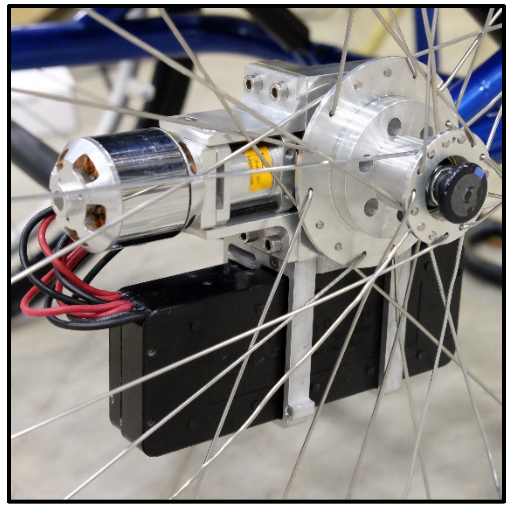

**Figure 47: System without Motor Shroud, Source: Own Work**

The motor shroud is also used to mount a hall sensor array which is a required input for the motor controller and is hidden on the inside of the shroud to prevent damage. The motor shroud mounts to a plate on the rear of the gearbox, and is vented to allow for some cooling during operation and allow for a window to monitor motor function during testing.

### 3.3.5. Other Design Requirements

The initial scope of the NeuwDrive system project was broad. It was recognized early in the ideate mode that all design requirements could not be fully addressed in the first iteration of the prototype. Specifically, the ability for the system to freewheel (design requirement 1.01) was not developed in this iteration of the prototype.

The ability for the system to freewheel is a requirement for the current gear system layout if the user wants to be able to seamlessly push the MWC when the system is turned OFF and still installed on the MWC. It was decided during the design process that integration of a clutch mechanism would decrease the available time and resources to successfully meeting other design requirements. Integration of a clutch mechanism is a detailed design problem, which can be addressed after a successful proof of concept design has been established.

## 3.4. Chapter 3 Conclusion

Chapter three encompasses the ideate and prototype modes of the design process. Using the design requirements from chapter two, a series of concepts were developed. These concepts were evaluated using the design requirements to determine a concept that would satisfy all needed performance outcomes. After development of a proposed concept, the project moved into the prototype mode to develop a physical representation of the design concept. A CAD model was constructed allowing for continued virtual iteration of different components of the design. Once all system components were selected and the CAD model was finalized, a series of engineering drawings were created and a prototype was fabricated.

The prototype combines several pragmatic concepts to realize the design requirements, including the use of inexpensive drivetrain components such as angle grinder bevel gears, hobbyist BLDC motors, and bicycle hub geometry. The result is a comprehensive prototype that addresses many of the design requirements, but also leaves detailed design work for future iterations. This prototype facilitated critical evaluation and testing in the subsequent test mode of the design process.

# Chapter 4. The Test Mode: Qualitative and Quantitative Evaluation of the NeuwDrive System

## 4.1. Introduction

The test mode in the Stanford Design Thinking (SDT) process is when feedback is solicited about the prototype that has been created from the intended user group. The test mode seeks to investigate beyond asking the user group if they like the prototype and instead ask “Why?” with the intent of learning more about the person and the problem as well as the developed solution. The test mode can then inform future iterations of the prototype [44].

Test mode may consist of both qualitative and quantitative testing. In the design of the NeuwDrive system, quantitative testing consisted of a series of tests that used the functional verification methods described in Chapter Two. The qualitative testing consisted of a focus group where the NeuwDrive system was presented to a group of PAW users who gave their feedback on the system. This chapter is separated into two parts that highlight the methods and results of both testing modes.

## 4.2. Quantitative Testing of the NeuwDrive System

### 4.2.1. Background

Dynamometer testing has been used for the testing of power assist wheelchairs (PAWs) [8], [68], [96] as well the evaluation of brushless DC (BLDC) motors for prototype PAW systems [97].An absorption dynamometer can measure the output angular velocity and torque of a PAW by absorbing the device's power using a hysteresis brake. Once the angular velocity and torque are known for a PAW, the propulsion force and linear velocity can be calculated from the radius of the drive wheel.

Verification of the torque and speed output of a prototype system using a dynamometer is important because it allows a designer to confirm that the prototype system is meeting the specified outputs. In the case of a system such as the NeuwDrive, dynamometer testing allows for monitoring the input voltage and current (e.g. input electrical power), as well as the output torque and velocity (e.g. mechanical output power). This provides a measure of efficiency for the system. The repeatability of dynamometer testing also allows for incremental controlled changes to be made to the prototype and to be able to study the impact of these changes separately.

Following ISO 13485 standards for design controls for medical devices, a prototype design must be verified against the stated design requirements. Quantitative, functional testing with measurable outputs required more rigorous testing to determine that the prototype design met the technical design requirements. Design requirements for a new modular power assist wheelchair system were developed by benchmarking existing systems (Table 15) and considering end user needs.

**Table 14: Technical Design Requirements**

| Number | Design Requirement | Rationale | Source | Verification Criteria | Verification Method |
|---|---|---|---|---|---|
| 3.01 | PAW must attain 9 km/hr | Same top speed as SmartDrive and Twion | IAP | Measurement | Run system on dynamometer |
| 3.02 | Continuous output torque of 21 Nm per wheel | Based on kinematic analysis of system requirements/product benchmarking | Analysis | Measurement | Tests on dynamometer |
| 3.03 | Must weigh less than 5.7 kg | Twion system is lightest on market at 5.7 kg | Literature Review | Observation/Team consensus | Measure mass of system |
| 3.04 | Output power of 60 W per wheel | Based on kinematic analysis of propulsion | Analysis | Measurement | Dynamometer testing |
| 3.05 | 20 km range | Based on other devices on market | IAP | Measurement | Dynamometer testing |
| 3.06 | System runs on 36 V DC | Compatibility with electrical systems | IAP | Functional Test | Check battery voltage |

### 4.2.2. Methods

Testing was completed to quantitatively validate the prototype design against each of the specific design requirements provided for the PAWs as mandated by ISO 13485 design controls.

#### ***Installing the NeuwDrive on the Dynamometer***

The NeuwDrive prototype was mounted on an ultralight MWC (Elevation, PDG Mobility, Vancouver, BC) for testing. The MWC was the installed on the dynamometer with the rear wheels positioned on the dynamometer roller. The front caster wheels were removed, and the caster forks were bolted to brackets that allow for the MWC to pivot about the caster fork. This allowed the rear wheels to rest on the roller and be subject to a normal force resulting from any weight installed in the MWC. To simulate an MWC user, 65 kg was placed into the MWC seat, and straps were used to secure the wheelchair frame to the dynamometer. The NeuwDrive prototype on the dynamometer is shown in Figure 48.

**Figure 48: NeuwDrive Prototype on Wheelchair Dynamometer, Source: Own Work**

### *NeuwDrive Testing Procedure*

The testing procedure of the NeuwDrive system copied the steady state testing method used for the SmartDrive in Chapter Two. The NeuwDrive was accelerated to its constant maximum speed of 10 km/hr with no braking torque. The recorded torque at this no-load condition included the resisting torque from the dynamometer friction. The dynamometer braking torque was then increased in approximately 2 Nm increments up to 12 Nm measured at the roller. At 12 Nm the drive wheel began to slip on the dynamometer roller, which provided an invalid result because the torque transfered to the dynamometer became a function of the dynamic friction of the NeuwDrive wheel and the dynamometer roller. During the testing increments, the NeuwDrive increased its torque output to overcome the braking torque, which resulted in a decrease in output speed until the system settled at a continuous power amount where the speed and torque were constant.

The results of the NeuwDrive testing were processed using a low-pass 2$^{nd}$ order Butterworth filter with a cut-off frequency of 1 Hz and then downsampled to 1 Hz (Matlab, Mathworks Inc). This filter and downsampling were selected based on the fact that the test were steady state and the system was maintained at a test torque value for greater than one second. The mechanical output power of the NeuwDrive was then computed by multiplying the torque and velocity. The specific metrics recorded and procedures for testing to validate each of the specific design requirements for the prototype are detailed below.

### *Design Requirement 3.01*

Technical design requirement 3.01 stated that the NeuwDrive must sustain a 2.5 m/s (9 km/hr) forward wheeling speed. The testing method for this requirement was to install the NeuwDrive-wheelchair device on the dynamometer and run the system at a continuous speed of 2.5 m/s. The angular velocity of the dynamometer roller was output by the dynamometer measurement system and this number was converted to a linear speed using the ratio of radii of the dynamometer roller (82.6 mm) and the NeuwDrive output wheel (304.9 mm) and equation 9. This calculation assumed no slipping between the wheelchair wheel and the dynamometer.

$$v_{MWC} = r_{wheel} \times \omega_{wheel} \quad (9)$$

### *Design Requirements 3.02 and 3.04*

Technical design requirement 3.02 stated that the NeuwDrive must reach a continuous output torque of 21 Nm. Based on the initial development of this design requirement in chapter two, the continuous torque of 21 Nm must be achieved at a linear speed of 0.83 m/s. The testing method for verifying this design requirement was to perform a steady-state dynamometer test where the resisting torque of the dynamometer was set to the equivalent of 21 Nm for the NeuwDrive wheel output. If the NeuwDrive could maintain or exceed a continuous speed of 0.83 m/s at the preset torque output of 21 Nm, then the design requirement was considered verified, and the system was functioning as designed.

Technical design requirement 3.04 stated that the NeuwDrive system must obtain an output power of 60 W per wheel. The same test that is used to verify the continuous torque output of the system is to verify the system output power, as the NeuwDrive is being run at a continuous torque and angular velocity, which translates into a continuous power output. Therefore, design requirements 3.02 and 3.04 were verified using the same test.

The torque and speed testing were not limited to testing the specifications laid out in the design requirements, but also tested the NeuwDrive over a range of continuous speeds and torques. Dynamic testing of the NeuwDrive was not performed as the dynamic response of the device will be related to the control method used, which has not been defined for the NeuwDrive system.

### *Design Requirement 3.03*

Design requirement 3.03 stated that each wheel of the drive system must weigh less than 5.7 kg. This design requirement was verified by weighing all components of the NeuwDrive system on a calibrated scale (Mettler Toledo 250 VF0021.r01 weigh scale).

### *Design Requirement 3.06*

Design requirement 3.06 stated that the NeuwDrive system must have a range of 20 km. This was based on the other available PAW systems on the market. The proposed method for verification of this design requirement was defined by the testing protocol used to test PAW system batteries, which was described in chapter two. The NeuwDrive was installed on the wheelchair dynamometer and run for a set distance of 0.89 km. The resisting torque of the hysteresis brake was set at 2 Nm to simulate a flat ground driving torque.  The time for completion of this test was recorded, as well as the battery current. All data was recorded using the software provided by the Phaserunner BLDC controller manufacturer, Grin Technologies (Vancouver, Canada). The average electric charge in ampere-hours used during the test was then calculated and input into equation 10 to determine the theoretical range in kilometers.

$$R = \frac{(C \times D)}{(E \times 1000)} \tag{10}$$

### 4.2.3. Results

#### ***Torque and Power Steady-State Testing***

Figure 49 and Figure 50 shows the results of the steady-state testing for the NeuwDrive system.

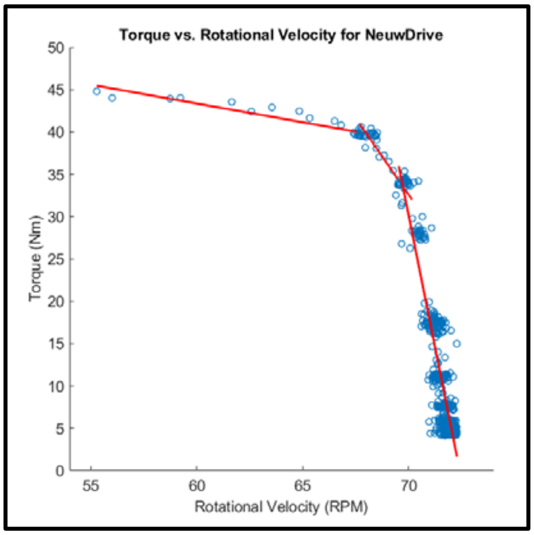


**Figure 49: Torque vs. Angular Velocity for NeuwDrive System, Source: Own Work**

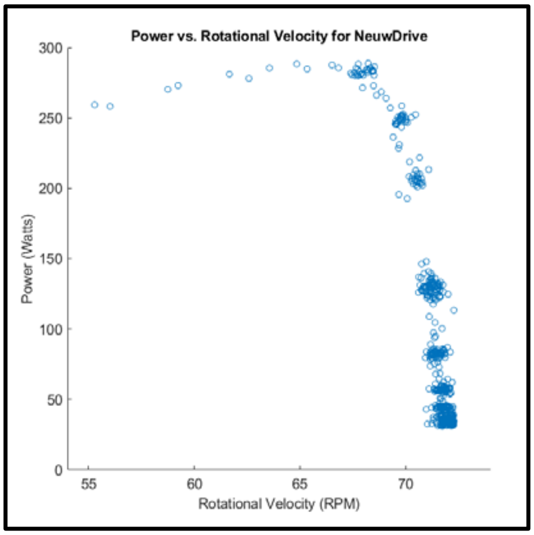


**Figure 50: Power vs. Angular Velocity for NeuwDrive System, Source: Own Work**

The maximum angular velocity of the output wheel was 72.2 RPM, which equals the equivalent linear speed of a MWC of 2.3 m/s (8.3 km/hr). The NeuwDrive system achieved a maximum continuous torque of 44.8 Nm at 55.3 RPM. All values described here were for one wheel. The continuous power at this torque was 259.4 Watts. This maximum continuous torque corresponded to a maximum linear propulsive force for a MWC of 146 N at 6.3 km/hr. The maximum continuous power of the NeuwDrive observed during testing was 288.8 Watts at 68.2 RPM.

The linear torque/speed relationship undergoes several changes throughout the data. This is primarily a result of the controller and battery settings of the system, which are limiting the allowed continuous power of the system. As a result, we observe a deliberate maximum in the steady-state power achieved by the system, as well as a limit on the maximum continuous output torque.

### *Battery Life Testing*

The battery life testing was performed for a total duration of 390 seconds, which equaled a travel distance of 890 meters. The average current consumption during this time period was 2.08 amperes. This equals an electric charge of 0.23 ampere-hours. The Grin Ligo batteries had an ampere capacity of 2.7 ampere-hours. Two batteries were used in the test for a total of 5.4 ampere-hours battery capacity. Based on equation 11 the theoretical range of the system is calculated below:

$$21\ km = \frac{(5.4\ Amphrs \times 890\ meters)}{(0.23 \times 1000)} \tag{11}$$

### *System Mass Measurement*

The system and all separate components mass are shown below in Table 15. The results are as expected, with the total system mass including the wheel equaling 5.1 kg. This mass is for one side of the MWC, as the complete NeuwDrive system would be made up of a left and a right drive.

**Table 15: NeuwDrive Component Masses**

| Component | Mass (kg) |
|---|---|
| Wheel | 1.84 |
| Batteries | 1.24 |
| Controller | 0.26 |
| Drive System | 1.76 |
| Total | 5.10 |

### 4.2.4. Discussion

The quantitative testing of the NeuwDrive system provided significant data to verify the design requirements and the built PAW prototype. Based on the results, the NeuwDrive system is exceeding the expected torque and power outputs compared to preliminary calculations. The tested maximum continuous torque saw a 114% increase over the preliminary calculations, and the continuous power at this tested torque saw a 355% increase over the calculation. In addition, the NeuwDrive mass has been minimized to the point that it is lighter than any dual-wheel PAW available on the market. Even though the NeuwDrive is still in the early development phase, the result of exceeding power output means that there is overhead in future iterations to reduce the power output. Reasons for decreasing the power output include minimizing the wear on the drive system components or installing a smaller, lighter BLDC motor or gear system. Knowing that the NeuwDrive prototype is currently exceeding expectations allows for future iterations to adjust design inputs to potentially satisfy other requirements.

During testing the NeuwDrive did not obtain the desired top speed of 9 km/hr, with the top recorded speed being 8.3 km/hr. This is primarily a function of the Phaserunner controller used in the NeuwDrive prototype, which did not allow for an exact means to control the output wheel speed. The Phaserunner controls the speed at the system input, in this case the BLDC motor, and then requires a multiplier based on the gear ratio to determine the wheel output speed. With testing and modification of the controller inputs or using a different controller, the desired speed of 9 km/hr could be achieved with the current drive system layout. The system achieved better performance in all other desired drive outputs, thus further optimization of the NeuwDrive system to attain higher drive speeds is also possible.

The total mass of the NeuwDrive system is 5.1 kg which is 0.6 kg less than design requirement 3.03. This represents a good achievement for a first prototype, as 0.1 kg could easily saved on the device through optimizing the gear housing or using a smaller BLDC motor. The measured mass included a rear wheel whose mass is comparable to a conventional rear wheelchair wheel. Rear wheels are required for the operation of a MWC, therefore a proper measure of the added mass of the NeuwDrive system would be to include the mass of all the components without the wheel. This lowers the mass of the NeuwDrive system to 3.26 kg. This complete NeuwDrive system requires a right and left side drive. This means that the total mass added to a MWC by the NeuwDrive system would be 6.52 kg. This total system mass is extremely competitive in comparison to the mass of available PAW systems. By comparison the SmartDrive system adds 5 kg. Twion system adds 12 kg (6 kg per wheel), though the Twion system includes the rim, spokes and tire of a regular wheel, so in reality adds approximately only 9 kg total to a MWC.

The NeuwDrive system exceeded the continuous torque requirement 3.02 and the continuous power requirement 3.04 by by 114% and 355% respectively. Design requirement 3.02 stated that the system must have a continuous torque of 21 Nm for one wheel. The NeuwDrive system during testing was able to achieve more than double this value, reaching a maximum output of 44.8 Nm during testing. This result is extremely promising, as it allows for a safety factor of 2 on the NeuwDrive’s output. This is important because no standardized driving durability test exists for PAW systems. PAW manufacturers currently select components of the ISO 7176:2014 Wheelchairs standards that are applicable for PAWs, but these tests do not mandate any durability testing or specifications. Further testing of the NeuwDrive in the field and real-world conditions, as well as accelerated life testing using the dynamometer represent further paths of exploration in the NeuwDrive development.

Similar conclusions can be drawn for design requirement 3.04, which states that the system must have a continuous power output of 60 W. The NeuwDrive system output a maximum continuous power of 288 Watts, and is currently exceeding the specified power requirement for all attainable drive speeds tested. It is important to recognize that the NeuwDrive was tested at torque/power values much higher than would be safe and necessary to drive the system. This was done to establish an upper limit on the device’s ability and to attempt to identify areas of potential failure. In addition the peak torque seen during acceleration which are up to four times the continuous torque (see Chapter Two “Defining Torque and Power Requirements) still needs to be tested regardless of the size of the RMS torque. The results of the testing are promising as they indicate that the NeuwDrive can meet both the continuous and peak power design requirements, and that future iterations could optimize the output power through improvement of the drivetrain, motor design or power electronics.

Design requirement 3.05 states that the NeuwDrive must have a 20 km range. Based on the battery life testing performed on the dynamometer, the NeuwDrive is meeting this design requirement. The battery life testing performed on the dynamometer is not a perfect simulation of real life as it does not include high-current accelerations that occur from the stopping and starting of a PAW system. Despite this imperfect test condition, the result is promising as the current test equaled to a range of 21 km. Further battery life improvement could come from an optimized BLDC motor or a more efficient motor controller,or slightly higher capacity battery.

### 4.2.5. Conclusion

A series of tests drawn from the verification procedures of the technical design requirements were developed to quantitatively test the NeuwDrive prototype. The system mass, battery life, torque output and power output were all verified using different measuring instruments including an absorption dynamometer. The NeuwDrive system did not meet the top speed design requirement and the total mass design requirement, but the results were close enough that further design iterations could improve the current specifications. In addition, the power and torque testing of the NeuwDrive system showed that the system is exceeding the design requirements by a factor of two. Therefore, future iterations of the NeuwDrive system could be improved through optimization of the drive system while simultaneously decreasing the total mass.

# 4.3. Qualitative Testing of the NeuwDrive System

## 4.3.1. Introduction

Power-assist MWC systems have now been available to MWC users for almost two decades. In this time, their uptake by MWC users has been considerable. In addition, the number of different power-assist systems has increased, and MWC users are now presented with a variety of options when selecting a power assist system. Despite the number of available options, very little research has been done to investigate the perceptions of power-assist systems by manual MWC users. An understanding of these perceptions is important because it provides the basis for the development of future designs of power-assist systems, and potential needed refinement of current systems.

As first highlighted in [98], the goal with holding a focus group as opposed to interviews would be to provide direct evidence about similarities and differences in the participants' opinions and experiences. A focus group also allows the researchers the ability to observe a large amount of interaction between participants all while directing the session to maximize feedback on the NeuwDrive system. In addition, a group of power-assist MWC users could be well positioned to provide feedback as they are experienced users who have tested and purchased various PAWs.

The purpose of this section is to explore the end user response to a prototype PAW system (the NeuwDrive) and related this feedback to the verification of the NeuwDrive design requirements.

### 4.3.2. Methods

Seven manual MWC users who had experience with power-assist devices were recruited to participate in a 1.5-hour focus group. Focus group participants were required to have used a power-assist system in either daily use or a research study in order to participate. They were recruited through word of mouth, flyers posted at local community centres, and community resources. Participants were asked to read and sign a consent form prior to participation, and to then fill out a demographics form prior to starting the focus group. This study was approved by the Offices of Research Ethics of Simon Fraser University and the British Columbia Institute of Technology.

The focus group questions were presented in two parts, with the first half hour of the focus group being dedicated to user perceptions of power assist, and the next hour being devoted to gaining feedback on the NeuwDrive system design. The user perception questions focused on gaining feedback from users on their previous experience with power-assist.

The NeuwDrive portion of the focus group had the goal of gaining feedback on the current prototype of the NeuwDrive system. The focus group began with a video demonstrating the NeuwDrive system driving on a MWC dynamometer. The installation and removal were then demonstrated live to the participants. Once the install was demonstrated, the questions were asked. The question protocol therefore progressed from more general questions to specific questions about the device and component functionality. The NeuwDrive feedback questions for the focus group were:

1. What are you first impressions of this solution?
2. How do you feel this system compares to the systems you have previously used?
3. What features of the NeuwDrive do you particularly like?
4. What features do you dislike?
5. What are your impressions of the installation / removal process?
6. What do you think about the battery removal/ attachment process?
7. Are there any physical aspects of using the NeuwDrive that may impact its usability?

The complete results of the focus group were transcribed and organized based on how it related to specific design features of the NeuwDrive system. The resulting feedback was then summarized, with examples drawn from the transcribed text. Thematic analysis was used to analyze the first part of the focus group dedicated to user perceptions of power-assist [99]. Common themes determined through the analysis included mobility, usability and psycho-social impact of PAWs. The second half of the focus group related to specific questions and feedback around the NeuwDrive system, and the themes were therefore the exact questions that were asked in the focus group.

### 4.3.3. Results

The demographic data of the participants is summarized in Table 16.

**Table 16: Participants Demographic Data**

| Participant | Age (years) | Number of years using a manual MWC | Power assist device use experience | Disability |
|---|---|---|---|---|
| P1 | 55 | 25 | SmartDrive MX2 | Amyoplasia. Level C5 incomplete |
| P2 | 30 | 25 | Firefly | Spina bifida (L4S1) |
| P3 | 42 | 22 | Twion | SCI, Level C5 |
| P4 | 43 | 1.5 | SmartDrive | Myalgic encephalomyelitis |
| P5 | 41 | 25 | SmartDrive, E-Motion, Batec, Firefly | SCI, C7 incomplete |
| P6 | 53 | 46 | Tested SmartDrive and Twion | SCI, T4 complete |
| P7 | 36 | 15 | SmartDrive | SCI, T4 complete |

## General Perceptions

Participants were immediately excited about the device, with the initial questions being centred on the device mass and the installation process. With the complete prototype weighing 3.31 kg for one side of the MWC including the rear wheel, participants were excited about the low weight.

Participants were concerned about the noise level of the NeuwDrive system though the movie shown was silent. One participant noted that quieter noise level was a key factor for choosing power-assist over a traditional power MWC.

## NeuwDrive Axle System

Participants were concerned about the impact of the NeuwDrive system on the MWC width. Participants noted that both the MWC width with both wheels on and the MWC frame width without wheels must be minimized as much as possible. Participants were happy that the NeuwDrive system did not increase the complete MWC width, but one participant expressed concern about the axle receivers of the NeuwDrive system, as they increase the MWC frame's width without wheels by 50 mm. Participant P5 was concerned that this added width would impact the ability to put their MWC in unexpected places, stating "when you're getting into your friend's car or whatever, if you're going wherever you're going, they can pop those wheels off easily but now they've got to put the frame of the chair into the trunk or wherever it's going to go so if it's creating a larger overall package size for the frame, that's going to make it harder to stow the chair when you're travelling or getting into somebody else's car."

## Removable Drive System Feedback

Participants had strong feedback regarding the ability to completely remove the NeuwDrive motor system and use only the wheels.  Many of the participants described that this functionality was not important to them, and that the only time they would remove the device from their MWC would be when they were performing a car transfer, traveling with their MWC on an airline, or had someone else remove the drive system to pull them up a set of stairs. One participant described how it was more important to them that the drive system did not add any resistance when switched off, stating that "if it could have zero … added resistance, when I turn it off, then I would just leave it on all the time and just turn it on when I want it."

Another participant noted that they do remove their SmartDrive from their MWC because they don't want the manually push with the extra weight and added resistance. Despite being comfortable removing their SmartDrive, the participant indicated that they would likely not remove the NeuwDrive system as it is more challenging to remove, stating that with the NeuwDrive "you have to pop the wheel off to take them on and off, so you still have to transfer out, take it off, and put it back on." Other participants indicated that they would not want to remove the device as it would lead to wear and tear on the shoulder from having to remove both wheels and two motors.

One participant indicated that they liked the ability to remove the whole motor assembly if need be but did not like the fact that the system required you to use a proprietary wheel/hub when the motor was removed. Participant P4 did state that they "like the ease of attachment, it seemed pretty easy to get it on and off."

**Battery System Feedback**

Participants were mixed in their response to the concept of removable and stackable batteries. Many participants liked the idea of being able to extend their range by adding a second battery. A participant liked being able to remove one battery to minimize the MWC weight. Another participant described other potential benefits: "I like the removable batteries particularly because you could have extra batteries and just leave them at home and attach them if you needed them or have them in the car."

A participant was initially skeptical of the stackable battery concept, stating: "I don't care about the weight, that's the thing, it's already on there. And then it pays for itself if it's charged up anyway. And then if the battery dies, it's pretty much neutral to me." Another participant did describe how removable batteries could be useful for charging the batteries. This was in regard to the Twion, which requires the whole wheel system to be near the charger while charging.

Participants were positive about a battery range that was the same as the 18 km range of the Twion and SmartDrive systems. All participants favoured fast charging ability, with the magnetic charging connectors of the Twion being suggested as one method for attaching the charging cable. Another participant pointed out that the magnetic charger works well for users with poor hand function as the cable just snaps into alignment. Other participants expressed interest in wireless charging as a possibility.

Valuable discussion centred on the placement and functionality of the battery position. Several participants suggested moving the battery compartments so that the batteries could be slid vertically into the system, allowing the MWC user to reach back and slide the battery in, rather than having to slide the battery away from the chair as in the current configuration. Other participants preferred the idea of a battery below the MWC seat, similar to the older SmartDrive MX1 battery location. One participant mentioned the possibility of integrating a USB port for charging a smartphone.

### Effect of Device on Chair Handling Feedback

Participants were vocal on the impact of the NeuwDrive system on the MWC's center of gravity. Another participant noted that a large part of the NeuwDrive's mass is behind the rear axle of the MWC, a placement which potentially impacts the center of gravity. This is important as a MWC user's MWC is set up to place their center of gravity in a position that is optimal for their specific wheeling characteristics.

### Device Control Feedback

Participants were in favour of designing the NeuwDrive to have selectable assist levels. The desired method of controlling the wheels for all participants was pushrim activated control, like the Twion system. All participants were in favour of the NeuwDrive system having regenerative braking.

Participants were mixed on having a smartphone application that could communicate with the NeuwDrive system. Participants like the idea of being able to check battery life and set assist level in an app. SmartDrive users in the focus group said that they never check usage data (e.g. number of pushes, distance traveled etc.) that is available through the SmartDrive app. Participants were not interested in route mapping being integrated into the app. PA participant expressed interest in integrating voice control into a smartphone application for controlling the wheels. They also expressed concern with having to open a smartphone application to change settings while simultaneously controlling power-assist wheels.

Table 17 summarizes the results of the device specific feedback from the focus group.

**Table 17: Results Summary**

| Category | Positive Feedback | Room for Improvement |
|---|---|---|
| General Perceptions | low weight | |
| NeuwDrive Axle System | Doesn't increase width | concerned about fitting frame in small spaces with protruding axles |
| Removable Drive System | system seems easy to take on and off | Participants would only remove drive system for transfers, participants did not like having to transfer out of WC to remove system, some dislike of proprietary hub system |
| Battery System | Extending range through multiple batteries, leaving batteries in separate locations, removable batteries useful for charging, | Wants included a magnetic charger, wireless charging, batteries in better location WC, USB charging port |
| Effect of Device on Chair Handling | | impacts tipping point of WC, adds mass |
| Device Control | | Could have selectable assist level, pushrim control, regenerative braking, smartphone app for settings, no usage data, no route mapping, dangerous to use app and steer |

### 4.3.4. Discussion

The focus group results provided user feedback into the prototype of the NeuwDrive system. The results of this study will help further inform a future iteration of the NeuwDrive system through the feedback obtained in regard to the design requirements. In addition, the focus group results included feedback that had not been considered previously in this project or other studies. This section discusses the focus group feedback in relation to the original design requirements and highlights areas for further exploration.

The lack of importance attributed to a removable drive system by the focus group participants came as a surprise to the investigators and emphasizes the value of end user feedback in the design process. The focus group feedback indicated that removing a mass such as a power-assist system when not in use was not important in their daily use of such a device. One reason could be that the NeuwDrive mass was perceived as so negligible that it would not significantly impact the mobility of the focus group participants. This comes with the caveat that, according to participants, the drive system should provide no resistance when manually pushing the MWC without power assistance (e.g. coast or freewheel). For the focus group participants, a heavier drive clutch mechanism that allows the system to stay on the WC rather than removing the drive system could have provided a better solution to requirement 1.01.

The concept of a removable battery system has been presented in other power-assist systems such as the Yamaha JW-II [100], as well as documented by Ramirez and Holloway as what power-assist users would envision in a ideal power-assist device [27]. This was captured in the define mode through design requirement 3.02; the batteries must be easily removed and installed. This requirement was further reinforced by our focus group findings, where participants were very positive toward the idea of a removable battery. This type of battery configuration has numerous potential benefits including being able to have batteries at separate locations such as work and home, as well as being able to remove the batteries when charging.

Not removing the batteries from the chair is a downside to a system like the Twion, as the user has to either remove themselves from their MWC while it stays at the charger with the Twion wheels installed or transfer from their MWC and remove the

Twion wheels, then install other wheels and transfer back while the Twion wheels charge. The only other option is for the user to plug in the Twion wheels at a point in their day where their MWC is going to remain relatively stationary, such as when the user is at a desk or going to bed. These options all have the potential to limit the user's mobility and independence. Based on the focus group findings having the batteries easily removed and installed is a valuable component of the NeuwDrive that was met with favourable feedback and should be maintained in future iterations

Design requirement 1.02 stated that the NeuwDrive must not increase the width of a chair beyond that of a conventional MWC. Participants in the focus group verified this design requirement by expressing the importance of minimizing the MWC width when possible. Further evaluation through focus groups or user testing of the protruding axle concept would be needed to determine if the additional width of the axle receiver has an impact on the MWC functionality when preforming car transfers etc. as was speculated by one of the focus group participants.

Other takeaways from the NeuwDrive feedback that agrees with information previously documented include more human factor requirements such as ease of use, intuitive control, and smartphone integration [27]. As current devices such as the SmartDrive enter their third iteration, their functionality becomes more mature and can better cater to user needs through device integration with other technologies such as smartphones and wearables. In addition, the development of technology such as lightweight portable lithium-based batteries are opening the possibility for designers to make power-assist devices more discrete and functional than ever before. At the same time, MWC users may now be more aware and accepting of new technology. This is highlighted by discussion in the group for features such as a USB charging port and wireless battery charging in the NeuwDrive system, two features which do not have any impact on device propulsion function but instead improve quality of use and experience for the user. Despite advancements in smartphone integration for devices like the SmartDrive, only some of the focus group participants thought this was of any value, with the primary underlying concern appearing to be having to rely on a smartphone to operate the device.

The feedback regarding the impact of the NeuwDrive system on the center of gravity of the MWC was an interesting highlight that was not captured in the design requirements during the define mode. The conversation of center of gravity is important from two perspectives: (1) The user/MWC system's center of gravity has an impact on the rolling resistance of the MWC, as a rearward weight bias puts more weight on the rear wheels and less on the front wheels [101]. (2) the position of the center of gravity can also impact the ability for a MWC user to perform a MWC wheelie [102], which is a critical skill for navigating bumps and objects in the built environment.In terms of future development of the NeuwDrive system, ideally further study of the impact of PAW on device handling could inform a series of future design requirements around the allowed impact of PAW on center of gravity and MOI. Without actual quantification of the impact of a PAW on handling it becomes difficult to capture the need in a design requirement, therefore further research is needed.

### 4.3.5. Conclusion

A review of current qualitative research investigating MWC power-assist was conducted. From this review, a focus group was designed and conducted with seven MWC users to gather user perceptions of MWC power-assist systems and gain real user feedback on the current prototype of the NeuwDrive system. The results of the focus group reinforced previous qualitative study findings on user perceptions. In addition, the prototype feedback reinforced some customer requirements and presented new areas of development and improvement for the NeuwDrive system. Assessing the device with a group of knowledgeable, engaged power-assist users brought up unique feedback that is invaluable to the engineering design process and will lead to revisions in the stated design requirements.

## 4.4. Chapter 4 Conclusion

Chapter 4 encompasses the test mode of the project. The NeuwDrive prototype was tested using both qualitative and quantitative methods to compare the built prototype to the design requirements. This is an important component of Stanford Design Thinking as it allows for prototype refinement, gaining more feedback from end users, and design problem redefinition. The results of the test mode will further inform future prototypes of the NeuwDrive system.

The results of the quantitative testing indicated that the NeuwDrive system met many of the expected technical design requirements and has enough overhead in the torque and power outputs to allow for optimization of other design requirements in future iterations of the prototype.

The resulting feedback from the focus group reinforced many of the design requirements, while also indicating new paths for further exploration. The group emphasized that a lightweight, powered-assist system that replaces regular MWC wheels and has no impact on regular wheeling when switched OFF is a market need that deserves continued development.

The results of the test mode indicate that there is room for improvement in the current NeuwDrive prototype, but that overall the system is satisfying the initial design requirements. The results of the testing have the additional benefit of demonstrating that the novel solutions that the NeuwDrive present are confirmed by actual users.

# Chapter 5. Discussion and Conclusions

## 5.1. The NeuwDrive System

Power-assisted wheelchair systems are a beneficial upgrade to a regular manual wheelchair that can potentially decrease injury [9] and potentially increase community participation [13], [14]. Several power-assisted wheelchairs exist on the market, but feedback and literature review has indicated that these devices are not meeting all user needs. As a result, a novel power-assisted wheelchair system was developed to better meet user needs. The resulting prototype is the NeuwDrive power-assist system.

The NeuwDrive is a unique system that incorporates two gear reductions to take advantage of lightweight, high-power brushless direct current motors. The prototype incorporates a spiral bevel gear sourced from low-cost components to demonstrate a novel drive layout that is discrete and minimizes impact on the wheelchair width and handling. An integral part of the NeuwDrive system is the unique flanged wheel that interlocks with the drive system but can act as a regular manual wheel when the drive is removed. The system incorporates removable batteries that allow the user to swap charged batteries at their convenience. The whole system weighs 5.1 kg for one side of the wheelchair, which is competitive with the class leading devices on the market.

Preliminary testing on a dynamometer demonstrated the prototype's ability to exceed several technical design requirements, highlighting an opportunity to further optimize power use and performance. A focus group presenting the NeuwDrive to a group of power-assist users brought favourable feedback that indicated that the NeuwDrive's features are desirable on the market and meet many of the functional design requirements. Focus group participants have confirmed that a lightweight, powered-assist system that replaces regular MWC wheels and has no impact on regular wheeling when switched OFF is a market need that deserves continued development

## 5.2. Design Challenges and Limitations

Specific limitations of the NeuwDrive prototype include the attachment mechanism, as it depends on the geometry of the specific MWC. This is only a limitation in the short term, as different brackets could be fabricated for specific wheelchair types. Another limitation of the current prototype was the use of hobbyist motors and gearboxes which may not be able to withstand the different use cases of a wheelchair drive system or may not meet the quiet sound requirements or the lifecycle requirements of a discrete PAW. This can be improved through the specification of a more expensive, more robust, quieter BLDC motor such as those manufactured by MAXON.

Another limitation of the NeuwDrive prototype in its current form is the lack of control system for detecting a user input and controlling the BLDC motor. It was recognized early in this project that the control of PAWs is an integral component of how these devices function, and for a device to be successful it needs to provide a control that is functional, intuitive and safe. The decision was deliberately made to not focus on control for this project and to instead focus primarily on developing functional hardware that combined human factors with mechanical design. As a result, the lack of control of the system is a current limitation and is an area for further development.

## 5.3. Future Work

Some components of the NeuwDrive system require further design if the NeuwDrive is ever to become a successful commercial product. Specifically, the current prototype was not able to address all initial design requirements. In addition, feedback from the focus group and the results of the quantitative testing showed that further refinement of the design requirements is needed. However, with concept of the NeuwDrive well-developed, this future work is mostly detailed design rather than complete concept redevelopment.

Design requirements that were tangent to the power assist mechanism were not emphasized in this initial prototype development. The focus on the initial prototype design was on the ability to create a small, light weight power assist system. Additional features such as freewheeling, and advanced controls only become important once a proof of concept has been established for the power assist design. The prototype NeuwDrive system has shown the potential to generate sufficient torque and power for functional power assist in a modular lightweight design. Therefore future work can focus on addressing the additional design requirements and refining the prototype design.

One design requirement that was intentionally downplayed in the current iteration of the prototype was a design requirement where the drive system would allow the wheel to freewheel. During the concept development of the NeuwDrive system, it was decided to design the current prototype with the ability to completely remove the drive system and install the manual wheel on its own. The rationale for this approach was that it would allow for the user to remove the motor drive in “free-wheeling” mode, thereby reducing the total system mass when they were now manually propelling.

The focus group feedback indicated that users are more interested in having some type of mechanism that allows for engagement/disengagement of the drive system, while keeping the drive installed on the chair, an idea we originally explored during the ideate mode. A future iteration of the NeuwDrive system could incorporate a lightweight clutch mechanism that is controlled by the user and allow the drive system to completely disengage from the output wheel. A future iteration of the NeuwDrive system should incorporate a clutch to investigate this desired feature and confirm its value towards a finished product.

The final area of future work includes the continued iteration of the NeuwDrive prototype to bring the design to a stage where it can be licenced and manufactured as a commercial product. This will require significant amounts of work, including ergonomic assessments, consultation of medical device and wheelchair standards, improved detailed design for the mechanical and electrical components, and further user testing. Based on the positive feedback of the focus group and the higher-than-expected device power and torque outputs, the NeuwDrive could have the potential to be a successful commercial product through continued iterative design and product development.

The NeuwDrive system is a unique prototype with real potential to impact the market. Continued development of the system through renewed design requirements and new iterations would allow for further testing that would put the device along the path to commercialization.

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# Appendix A.

### *GearBox Types Overview*

The purpose of a gearbox is to change the torque and speed of an input to a value that is suitable for the driven output. Gear reductions result from a difference in pitch diameter of two or more gears. Gearboxes come in a variety of orientations and reduction ratios based on the desired characteristics of the system. The following section will detail some gear types that are applicable to a reduction system.

The most common and simplest of gear types is the spur gear. Spur gears are used to transfer motion between parallel shafts, and they have teeth that are parallel to the shaft axes [87]. Figure 51 shows an illustration of a spur gear set.

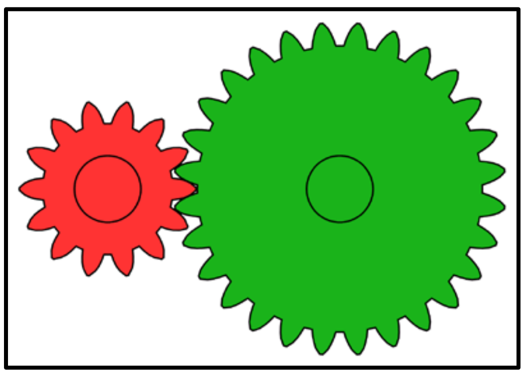

**Figure 51: Spur Gear Set** [103]

A reduction gear operates under the principle of an angular velocity ratio between two meshing gears of differing radius. The angular velocity ratio results from the linear velocity of both gears being equal at the line of action between the gears. The smaller gear is typically called the pinion. The reduction ratio of a gear set can be calculated using equation 12, where $\omega$ is the angular velocity, $r$ is the gear radius and $N$ is the number of teeth on the gear.

**12**

$$\frac{\omega_{pinion}}{\omega_{gear}} = -\frac{r_{gear}}{r_{pinion}} = -\frac{N_{gear}}{N_{pinion}}$$

The simplest of gear reductions is achieved by maximizing the output gear diameter while simultaneously minimizing the pinion diameter. However, this approach alone can cause issues including tooth breakage, oversized output gears, and increased wear on the pinion gear. As a result, gear reductions can be coupled into multiple stages, where each stage represents a separate reduction that contributes to a complete reduction between input and output shaft that is calculated by analyzing the torque and angular velocity intermediate shaft.

An extension of the spur gear reduction gear train is planetary or epicyclic gearing, shown in Figure 52. The primary use of a planetary gear set consists of a sun gear at the center, several planet gears that rotate about the sun gear, and a ring gear that contains the planet gears. The incorporation of multiple planet gears balances the transmitted forces between each planet gear, thereby minimizing the force on each planet gear and providing a robust gear train with a reduction ratio. Planetary gears can be combined in multiple stages for further multiplied reduction [87].

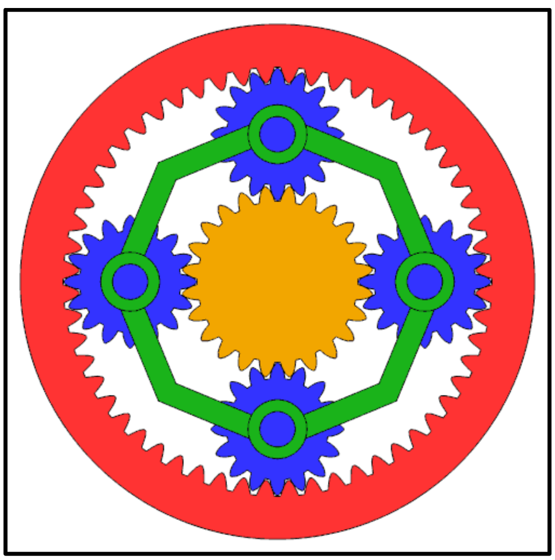

**Figure 52: Planetary Spur Gear Set** [104]

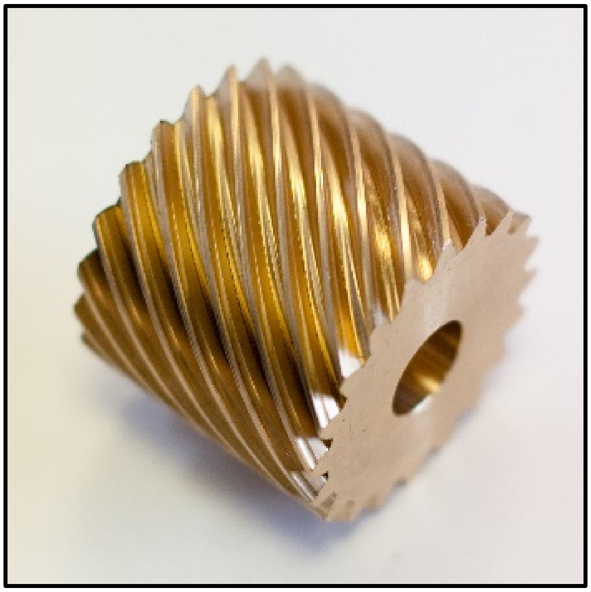

**Figure 53: Helical Gear, Licensed under CC BY-NC-ND 2.0, Author: Haukur Herbertsson** [105]

Variations on the spur gear tooth form exist. The helical gear is like a spur gear but has the teeth angled about the circumferential face of the gear. As helical gears rotate, the tooth contacts spreads along the longer face of the gear tooth, which makes for smoother and quieter operation, as well as higher achievable rotating speeds. The angled face of helical gears results in a thrust load being transferred to the input and output shaft which must be accommodated for in mechanical design [87]. A helical gear is shown in Figure 53.

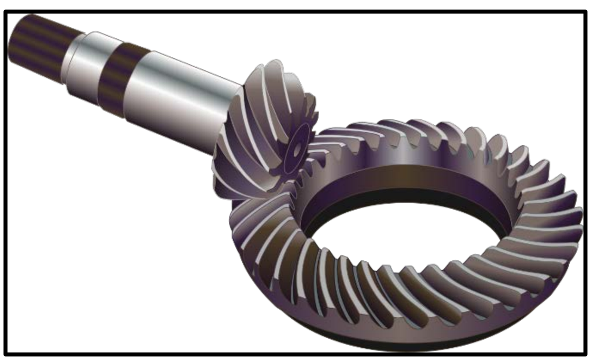

**Figure 54: Spiral Bevel Gear** [106]

The bevel gear has tooth surfaces made up of conical elements for the purpose of allowing non-parallel shafts to be coupled. The teeth of a bevel gear can be straight or spiral, with spiral teeth engaging more gradually and allowing for smoother and quieter operation. Bevel gear shafts are typically perpendicular, but a variation on the bevel gear called the hypoid gear allows for non-perpendicular shafts [87]. A spiral bevel gear is shown in Figure 54.

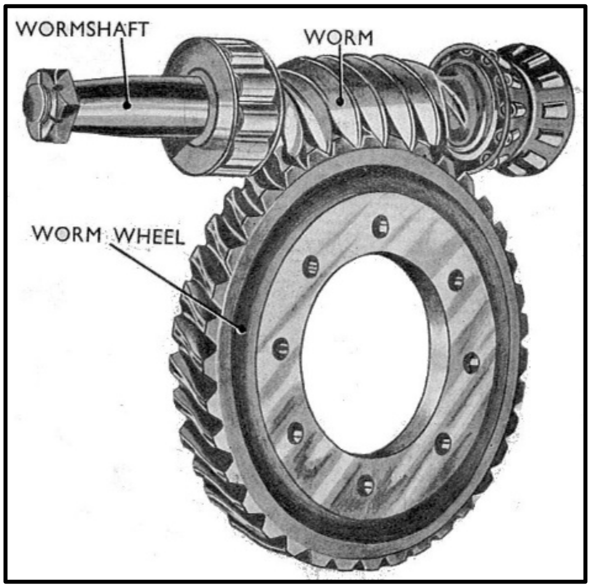


**Figure 55: Worm Gear Set** [107]

A worm gear set is essentially a screw meshing with a special helical gear [87]. Worm gear sets are made up of the worm input and the worm wheel output. Worm gear sets are characterized by large velocity ratios (up to 300 or more) and high sliding velocities. The geometry of a worm gear set can be designed to be non-overhauling (self-locking), meaning that no amount of torque on the worm gear output can produce motion [87]. A worm gear set is shown in Figure 55.