WHEELCHAIR FIT SETUP EFFECTS ON PATIENT-REPORTED OUTCOMES AND BIOMECHANICS: AN INTERDISCIPLINARY ANALYSIS ON USER-CENTERED APPROACH OF WHEELCHAIR USE

by

Brian Patterson

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ABSTRACT

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This thesis investigates the impact of wheelchair fit metrics on propulsion mechanics and functional outcomes in manual wheelchair users with spinal cord injury (SCI) and spina bifida (SB). Ensuring proper wheelchair fit is crucial for optimizing propulsion, comfort, and reducing the risk of injury, especially overuse injuries in patients with spinal cord injury and dysfunction (SCI/D). This project sought to explore and add to literature surrounding the associations between wheelchair fit, patient-reported outcomes (PROs), and propulsion dynamics. This was done by correlating wheelchair fit measures with patient-reported outcomes, elbow angles at top dead center (TDC) and propulsion dynamics. Several group comparisons were also made between adult- and pediatric-onset groups to determine the effect of onset in wheelchair fit, PROs, and propulsion dynamics.

Participants completed patient-reported outcomes questionnaires on pain, pain interference, and independence. Using three-dimensional motion capture, quantitative measurements of their wheelchairs were recorded, and propulsion biomechanics were analyzed. The participants were all adults with SCI/D and were separated into adult-onset and pediatricnset groups to explore the differences between the two groups. The project focused on several wheelchair fit measures, including horizontal axle position (HAP), vertical axle position (VAP), backrest height (BH), seat width (SW), and seat dump angle (SDA). The PROs assessed were Wheelchair User's Shoulder Pain Index (WUSPI), Spinal Cord Independence Measure Version III (SCIM-III), and the Patient-Reported Outcomes Measurement Information System (PROMIS) Adult Pain Interference Short Form 8a. Conservative, non-parametric statistical analysis was used due to the lack of normality in the data set and the small sample size. Spearman's methods were used for correlation analysis and Wilcoxon rank sum methods were used for group comparisons.

One of the key findings of the project was that vertical axle position had a significant positive correlation with PC-WUSPI and PROMIS pain interference scores. It was also determined that the 3D flexion-extension elbow angle had a significant negative correlation with VAP. There was also a significant difference in PROMIS pain interference scores between onset groups, with the adult-onset group having more pain interference than the pediatric-onset group.

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CHAPTER 1 - INTRODUCTION

LITERATURE REVIEW

Spinal cord injury (SCI) and spina bifida (SB) are two distinct medical conditions affecting the spine which can result in varying degrees of motor and sensory impairments (Mayo Clinic, 2023; Bowman, 2001). Although these are distinct conditions, these two impairments are comparable in how they impact the function of the lower extremities. Being affected by SCI or SB usually necessitates the use of a manual wheelchair for mobility due to loss of function in the lower limbs – also known as paraplegia (NSCISC, 2012; Bowman et al., 2001). Paraplegia is a chronic impairment that causes partial or complete paralysis of the lower part of the body – including the legs, feet, toes, and even the trunk and some abdominal organs (Mayo Clinic, 2023). It is estimated that there are anywhere from 65 to 75 million individuals that use wheelchairs worldwide and around 3.3 to 3.5 million in the United States (WHO, 2023; Ott et. al., 2023). Manual wheelchair propulsion is a fundamental skill for individuals with SCI or SB because it plays an important role in enabling their mobility and independence. Due to the amount of time spent seated for manual wheelchair users (MWUs), there should be a focus on wheelchair fit, as it can affect both propulsion mechanics and comfort (De Groot et al., 2010, Harms, 1990). Comfort is especially relevant when considering cushions and, more broadly, seating due to the increased risk of pressure ulcers in MWUs (Sprigle et al., 2019). Additionally, the complete or partial loss of trunk control and the resultant negative impact on postural stability can cause individuals with paraplegia to need additional support on their seating (Alm et al., 2003). For individuals affected by paraplegia, the ability to propel a manual wheelchair efficiently, effectively, and comfortably is not only essential for daily activities but can also significantly influence their overall quality of life.

Medical Diagnoses

Spinal cord injury (SCI) is a neurological condition often caused by trauma, such as accidents or falls, or non-traumatic issues such as tumors or vascular problems. The severity of SCI can vary, leading to partial or complete loss of motor and sensory function below the level of injury (NINDS, 2020; Marino et al., 2003). Manual wheelchair propulsion is a primary mode of mobility for many individuals with SCI, with 39% of individuals with SCI choosing to use a manual wheelchair, making it crucial to examine the factors that affect their ability to propel a manual wheelchair efficiently and safely (NSCISC, 2021). Along with the physical manifestations of the condition, individuals with SCI can also exhibit psychosocial difficulties. Some psychosocial factors that are often considered in this population are quality of life and life satisfaction, self-efficacy and independence, body image and identity, and community integration and participation (Hallin et al., 2000). Due to the permanent nature of SCI, these factors should be considered when thinking about long-term outcomes in this population.

The American Spinal Injury Association (ASIA) Impairment Scale (AIS) is a standardized system used to classify the severity of spinal cord injuries (SCI). It assesses motor and sensory function to determine the level of injury and the degree of impairment (Marino et al., 2003). The AIS is divided into five categories: A (complete injury with no motor or sensory function below the level of injury), B (incomplete injury with sensory but no motor function preserved), C (incomplete injury with motor function preserved but most key muscles below the injury level having a muscle grade less than 3), D (incomplete injury with motor function preserved and most key muscles below the injury level having a muscle grade of 3 or more), and E (normal motor and sensory function). This classification is crucial for diagnosing SCI severity, guiding treatment, and predicting recovery outcomes (Kirshblum et al., 2011; Marino et al., 2003).

Spina bifida is a congenital defect that occurs during early fetal development in the neural tube (Bowman, 2001). The defect results in an incomplete closure of the spinal column and there also tends to be other complications in conjunction with the main impairment, such as hydrocephalus. SB can lead to varying degrees of motor and sensory impairment based on the level of the lesion, with some individuals having relatively preserved lower limb function and others experiencing complete paralysis (Ouyang et al., 2007). Regardless of the level of impairment, like those with SCI, many individuals with SB rely on manual wheelchairs to facilitate their mobility and independence (Boninger et al., 2005). Due to the similarities in how the two disorders manifest physically, there are also similarities in how they can affect functional outcomes – especially those factors which are impacted directly by wheelchair use (Holmbeck and Devine, 2010). However, there seems to be some differences in functional impact of the disorders due to the congenital nature of spina bifida and one potential impact could be the development of more effective coping mechanisms in living with spina bifida (Sawin et al., 2009).

Patient-Reported Outcomes (PROs)

Considering that manual wheelchair propulsion can have profound implications on functional outcomes, affecting an individual's self-identity, participation in social activities, and overall quality of life, it is summarily important to study these impacts (Rimmer et al., 2005). Exploring the functional outcomes of wheelchair use in individuals with SCI and SB is critical for developing an understanding of not only the physical implications of manual wheelchair use but also the impact on emotional and social well-being. This research will incorporate an analysis of patient-reported outcomes to gain insight into the subjective experiences of MWUs and how they may be influenced by wheelchair fit. The Wheelchair User's Shoulder Pain Index (WUSPI), the Patient-Reported Outcomes Measurement Information System (PROMIS) Adult Pain Interference Short Form 8a, and the Spinal Cord Independence Measure Version III (SCIM III) tools were used to evaluate shoulder pain, pain intensity, pain interference, function, and independence among individuals with SCI and SB (Wang et al., 2019). These were selected because they are established, National Institute of Health recommended, Common Data Elements from the National Institute of Neurological Disorders and Stroke (NINDS, 2024).

The WUSPI tool is a validated assessment which was specifically designed to assess shoulder pain and dysfunction specifically among individuals who use wheelchairs (Curtis et. al, 1995). It was developed to address the unique challenges and musculoskeletal issues which are faced by manual wheelchair users (Curtis et al., 1995). The following is an example of a question that was presented in the questionnaire: “Over the past week, how often have you experienced shoulder pain while performing wheelchair-related activities, such as pushing your wheelchair uphill or transferring in and out of your wheelchair?”. The subjects or participants answer questions like this on a scale of 1-10. The WUSPI tool was assessed to examine test-retest reliability and validity. It was determined that there was enough evidence to indicate that WUSPI is a reliable and valid tool that can be used to assess shoulder pain and dysfunction in wheelchair users (Finley and Rodgers, 2004). Overall, WUSPI is a focused tool for clinicians and researchers to assess and monitor shoulder pain at specific points in time, as well as over longer periods of time.

The SCIM III is an assessment tool designed specifically to evaluate the functional independence of individuals with SCI. Researchers conducted a validation study of the SCIM III, confirming its reliability, validity, and sensitivity to change in SCI patients (Catz et al., 2007). SCIM III is tailored to the unique needs and challenges faced by individuals with SCI or similarly manifesting disorders. The SCIM III evaluation tool covers various domains including self-care, respiration and sphincter management, and mobility. An example of a question asked in the SCIM III questionnaire is: "How much help do you need to get dressed?" with each individual domain scored separately and then summed to provide an overall score. SCIM III is a valuable resource for assessing functional independence in SCI patients, with strong evidence supporting its reliability and validity in both clinical settings and research.

PROMIS is a system of patient-reported outcome measures which were developed to assess various aspects of physical, mental, and social health across different populations and conditions. Researchers conducted a validation study of the measures included in PROMIS and the findings supported the reliability, validity, and responsiveness to change of the PROMIS tool (Cella et al., 2010). Unlike WUSPI and SCIM III, this measure is not specific to MWUs and is therefore more generalizable. The questions posed in PROMIS cover a wide range of domains such as physical function, pain, fatigue, emotional distress, social activities, and quality of life – but the question set used in this study is focused on pain interference. An example of a question asked in the PROMIS – pain interference measure is: "Over the past 7 days, how much did pain interfere with your day-to-day activities?". These questions were answered on a scale from “Not at all [1]” to “Very much [5]” with the sum of all the answers becoming a “raw score” that is later converted to a measure that can be used to draw comparisons. PROMIS is a resource for assessing patient-reported outcomes across a wide range of health domains and disorders, with evidence that supports its reliability, validity, and utility in clinical practice and research.

Manual Wheelchair Use

Although the functional outcomes of wheelchair use are certainly important, these factors are not the only contributors to life using a wheelchair. Due to the symptomology of SCI/D, these conditions usually necessitate the use of a manual wheelchair for mobility. Manual wheelchair propulsion is a complex motor skill that involves a combination of upper body strength, coordination, and endurance (Koontz et al., 2009; Schnorenberg et. al., 2014). Understanding the unique challenges faced by individuals with SCI and SB in manual wheelchair propulsion is essential for optimizing their functional independence and overall well-being.

Biomechanical analysis of manual wheelchair propulsion can be used to identify factors that may contribute to inefficient propulsion techniques, upper limb overuse injuries, and long-term musculoskeletal complications (Gorgey and Dudley, 2007; Leonardis et. al. 2023, 2024; Cordes et. al., 2024). By studying the biomechanics of wheelchair propulsion in individuals with SCI/D, we can develop targeted interventions to improve propulsion efficiency and reduce the risk of secondary complications. It is known that high repetition, or an increased cadence, contributes to overuse injuries in wheelchair users (Mason et al., 2020). Studying these complex motions is immensely important to understanding how individuals navigate their environments, and it is made easier via the use of motion capture (Harris, 1996; Whittle, 1996). Motion capture is a crucial tool for studying wheelchair propulsion due to its ability to precisely capture the biomechanical movements via the use of near-infrared (NIR) technology. Motion capture technology is useful for accurately recording three-dimensional (3D) positional data and can be used in the context of wheelchair propulsion to record difficult to measure data such as push angle and 3D joint angles over time. This study also utilized motion capture to take measurements of the wheelchair to record wheelchair fit variables with the same methodology each time.

Another important factor in wheelchair use that is often studied is kinetics. Specifically, peak resultant force is a critical measure in wheelchair kinetics because it directly impacts the efficiency and safety of wheelchair propulsion (Boninger, 2005; Richter, 2007)). By measuring the peak forces exerted on the hand rim, researchers and clinicians assess the mechanical load placed on the user's upper extremities. This assessment is important because excessive force can lead to repetitive strain injuries that are common amongst manual wheelchair users (Cowan, 2009). Understanding peak resultant force allows for the seating professionals to optimize wheelchair setup and design with the goal of reducing the physical demands of the user. Lowering peak forces through ergonomic improvements, such as adjusting the horizontal axle position, can enhance propulsion efficiency, reduce the risk of an overuse injury, and potentially improve the wheelchair user's mobility and quality of life long-term (Boninger, 2005). Ultimately, analyzing and mitigating peak resultant force is crucial for sustainable wheelchair use and minimizing the risk of injury.

Additionally, another important aspect of manual wheelchair use is the user's ability to engage in physical activity. Physical activity is essential for the health of manual wheelchair users, positively influencing cardiovascular fitness, muscle strength, and overall quality of life (Kehm & Kroll, 2009). Physical activity can profoundly affect a manual wheelchair user's outcomes (Fasipe et. al., 2024). Moreover, physical activity enhances mental well-being, fostering greater independence and active participation in daily life, including work and social activities. Holding a job can also have similar impacts. Occupational participation not only allows the MWUs to generate an income, but also enhances the user's sense of purpose, and can positively impact mental health and quality of life (Tremblay and Colley, 2010).

Manual Wheelchair Fit

Individually tailored wheelchair fit variables are critical for optimizing comfort, stability, and efficiency during manual wheelchair propulsion. Factors such as seat width, seat depth, backrest height, and rear axle position can significantly impact a user's ability to achieve an efficient push and minimize the risk of overuse injuries (Routhier et al., 2003; Boninger et al., 2005). For example, rear-axle position is a widely studied wheelchair variable. Previous studies have shown that the rear axle position can impact factors such as propulsion frequency, push angle, and even comfort (Boninger et al., 2000). This thesis will also explore the influence of wheelchair fit on manual wheelchair propulsion in individuals with SCI/D.

To understand wheelchair fit, the processes of wheelchair provision should be explained. The first step in wheelchair provision is the selection of the chair. The MWUs needs and preferences are to be explained and define via an individual assessment – this allows the clinician and user to select potential chairs that are appropriate. Then, the wheelchair and wheelchair accessories, like the cushion and backrest, should be fine-tuned so that they offer a custom fit that aligns with the user's comfort preferences and needs. After the chair has been fit to the specifications of the user, training should be given to both the user and any individuals

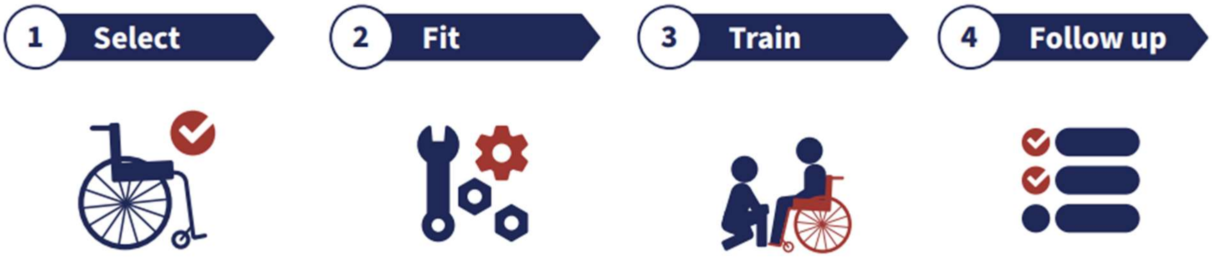


Figure 1: A flow-chart depicting the four wheelchair service steps. Courtesy of the 2023 World Health Organization's Wheelchair Provision Guidelines (WHO, 2023).

who may be supporting them. This step is crucial to maintain the chair and improve the user's functioning in the device. Lastly, follow up appointments should be conducted with a clinician or seating professional to ensure that the wheelchair continues to function as intended and to check in on the overall user-device integration (WHO, 2023).

The horizontal axle position refers to the distance between the rear wheels of the wheelchair and the user's body, impacting wheelchair propulsion biomechanics and shoulder loading (Boninger et al., 2005). Optimal axle position is essential for reducing the risk of shoulder injuries and discomfort by promoting efficient propulsion mechanics and minimizing excessive shoulder loading. Research has shown that a more anterior axle position (more forward) can result in decreased shoulder loading and improved propulsion efficiency, thus enhancing patient-reported outcomes related to comfort and shoulder health (Morrow et al., 2010; Lafta et al., 2018). A study by Richter et al. also demonstrated that variations in axle position significantly impacted propulsion biomechanics, restating the importance of axle positioning for propulsion mechanics (Richter et al., 2007).

Backrest height and backrest angle are related to trunk stability, posture, and can impact upper body biomechanics during propulsion. A properly adjusted backrest can reduce the risk of shoulder injuries and discomfort by promoting an upright seated posture and distributing forces more evenly across the upper body (Yang et al., 2012). Yang et al. also found that a lower backrest height increases range of motion during propulsion and therefore reduces cadence and repetition.

The other wheelchair fit measure that will be analyzed in this thesis project is seat width. Seat width refers to the dimensions of the wheelchair seat and/or cushion. This interface can influence user comfort, posture, and pressure distribution (Alm et al., 2003). Proper seat dimensions are crucial for reducing the risk of pressure ulcers and discomfort among wheelchair users, which are significant patient-reported outcomes. Additionally, optimal seat width and depth facilitate proper pelvic positioning, enhancing stability and propulsion efficiency during wheelchair use. Research by Sabari et al. (2016) found that inappropriate seat dimensions were associated with increased risk of pain and discomfort among wheelchair users. It is key to note, however, that even though a certain adjustment to wheelchair fit may be ideal on paper, it may not be beneficial for every person's circumstances. So, wheelchair fit needs to be approached on an individual level with a focus on personalization, but still backed by evidence-based standards.

Besides the physical design of the wheelchair and the spaces that they are used to navigate through, the role of reducing societal barriers to people with disabilities will also help with integration, participation, and other outcomes. A big help in this domain is educational programs and awareness campaigns that seek to inform the populace, reduce stigma, and shift public perceptions about wheelchair users. These initiatives need to continue to enlighten society's views on wheelchair users and therefore foster a more welcoming community. Although the social impacts of wheelchair use were not investigated in detail for this thesis project, it remains an important and salient aspect of wheelchair use.

Even though there is extensive research into how wheelchair fit can impact propulsion biomechanics, patient-reported outcomes, and comfort, there is a lot of disagreement on which factors are most important for wheelchair provision. This thesis will provide an examination of manual wheelchair fit in individuals with SCI and SB, drawing on a multidisciplinary approach that encompasses biomechanical, ergonomic, and factors that affect functional outcomes. The objective of this thesis is to contribute to evidence-based, user-centered wheelchair fit recommendations which enhance the health and quality of life of manual wheelchair users.

Problem Statement

Wheelchair provision is guided by both evidence-based decisions, such as adjusting backrest height based on level of injury, residual function and strength, and the user's individual preferences for comfort and usability. Despite a growing awareness around the importance of user-centered wheelchair fit for optimal function, the clinical community faces a substantial challenge due to the absence of a universally accepted set of wheelchair fit guidelines. Current literature highlights the lack of a clear standardized approach in wheelchair prescription practices, leading to concerns about the impact of varying wheelchair fit measures on health (WHO, 2023).

This thesis project seeks to investigate the associations between wheelchair fit, biomechanics, and pain and independence through the following aims:

Aim 1: To determine the relationship between wheelchair fit measures, self-reported pain and independence. Manual wheelchair users often experience musculoskeletal pain, and the most common pain area is the shoulder. Many MWUs attribute their pain directly to the set-up of their wheelchair (Liampas et al., 2021; Frank et al., 2012). It is hypothesized that certain wheelchair fit measures contribute significantly to self-reported pain. The measures that will be assessed are the horizontal and vertical axle position, backrest height, and the seat dump angle. Spearman's rank correlations will be applied to investigate the association among the wheelchair set-up variables and the performance corrected WUSPI, PROMIS pain interference, and SCIM III scores.

Aim 2: To determine the relationships between wheelchair fit measures (seat width, vertical axle position, and horizontal axle position) and flexion-extension elbow angle at top

dead center (TDC). Horizontal axle position is known to affect elbow joint angles (Collinger et al., 2008). This thesis hypothesizes that axle positioning and seat width will contribute to optimal elbow joint angles in the sagittal plane.

> **Sub-Aim 2a:** After determining the participants who exhibit optimal elbow positioning at TDC (Aim 2), this project aims to compare group differences between the optimal and non-optimal elbow position groups. Both traditional 2D and novel 3D methods will be deployed. It is hypothesized that there will be differences in WC fit variables relating to elbow positioning and between PROs of the performance corrected WUSPI, PROMIS Pain Interference Short Form and the SCIM III.

Aim 3: To examine the relationships between wheelchair fit measures (horizontal axle position and backrest height) and cadence and peak resultant force during propulsion. The wheelchair fit measures of interest for this aim are backrest height, vertical axle position, and horizontal axle position. Backrest height is known to impact range of motion during propulsion, which in turn impacts the length of stroke and cadence (Yang et al., 2012; Boninger et al., 2005). It is also widely accepted that repetition, which is influenced by cadence, contributes to overuse and over exertion injuries in wheelchair users (Mason et al., 2020). It is hypothesized that backrest height and horizontal axle position will be associated with cadence and peak resultant force.

Aim 4: To determine group differences in patient-reported outcomes, WC fit variables, and kinetics between adults in adult-onset and pediatric-onset groups. Personalized rehabilitation and wheelchair provision based on age can help lead to better WC fit, rehabilitation outcomes, and PROs. This aim will be investigating the difference between onset groups based on current knowledge that PROs and kinetics differ by age of onset of SCI/D.

Aim 5: Perform exploratory analysis on "torso height to wheel size ratio" and "shoulder width to seat width ratio" as a predictor of pain (PC-WUSPI, PROMIS) and independence (SCIM III).

CHAPTER 2 – MANUSCRIPT

Investigation of Wheelchair Fit and Patient-Reported Outcomes of Pain and Independence in Manual Wheelchair Users.

(a version of this chapter is in preparation for submission to a journal)

INTRODUCTION

An estimated 65 to 75 million people globally, including 3.3 to 3.5 million in the United States, use wheelchairs (WHO, 2023; Ott et al., 2023). Although it is unclear exactly how many individual manual wheelchair users there are, the National Spinal Cord Injury Statistical Center estimates that of those with mobility issues relating spinal cord injury (SCI), 39% use a manual wheelchair. Individuals with spinal cord injury and disorders (SCI/D), including spinal cord injury and spina bifida, rely on manual wheelchairs for mobility. Spinal cord injury (SCI) and spina bifida (SB) are distinct, yet result in similar conditions of the spine, leading to motor and sensory impairments often requiring the use of manual wheelchairs for mobility. Ensuring proper wheelchair fit in this population is vital for optimizing propulsion mechanics and comfort, as well as reducing risk of injury or pain interference (De Groot et al., 2010; Harms, 1990; Sprigle et al., 2019; Alm et al., 2003). The functional outcomes of manual wheelchair use, like pain interference or quality of life, are salient and should be addressed alongside the physical aspects of wheelchair use (Hallin et al., 2000).

SCI typically results from traumatic incidents or non-traumatic issues such as tumors, leading to varying degrees of motor and sensory function loss (NINDS, 2020; Marino et al., 2003). This condition also brings psychosocial challenges, including changes in body image and community integration. SB, a congenital defect causing incomplete spinal column closure, results in similar impairments but differs in psychosocial impacts due to its congenital nature, potentially leading to the development of more effective coping mechanisms (Sawin et al., 2009). SCI, SB, and other similar conditions are often referred to collectively as spinal cord injury or disorders (SCI/D). Understanding these psychosocial outcomes is crucial for enhancing the emotional and social well-being of wheelchair users. Functional outcome measures are also important to understanding the holistic impact of manual wheelchair use. Tools like the Wheelchair User's Shoulder Pain Index (WUSPI), Spinal Cord Independence Measure Version III (SCIM III), and the Patient-Reported Outcomes Measurement Information System (PROMIS) Pain Interference Short Form 8a are used to assess shoulder pain, functional independence, and quality of life, providing valuable insights into the experiences of these individuals (Curtis et al., 1995; Finley and Rodgers, 2004; Catz et al., 2007; Cella et al., 2010).

The biomechanics of wheelchair propulsion are intricate, involving upper body strength, coordination, and endurance (Koontz et al., 2009; Cordes et. al., 2024; Leonardis, 2022, 2023). Biomechanical analysis, aided by tools like motion capture, helps identify factors affecting propulsion efficiency and the risk of injury (Gorgey and Dudley, 2007; Schnorenberg, 2014). Personalizing one's wheelchair fit, considering variables such as rear axle position, backrest height, and seat dimensions, is crucial for optimizing propulsion and preventing injury (Routhier et al., 2003; Boninger et al., 2005). Research indicates that adjustments, such as more anterior axle positions and appropriately angled backrests, can significantly enhance propulsion mechanics and reduce shoulder strain (Morrow et al., 2010; Lafta et al., 2018; Richter et al., 2007; Yang et al., 2012). However, wheelchair fit must be tailored to individual needs, combining evidence-based standards with personal circumstances (Sabari et al., 2016). This objective of this project aims to ultimately improve the health and quality of life for manual wheelchair users by offering evidence-based recommendations for wheelchair fit, considering biomechanical, ergonomic, and factors affecting functional outcomes.

METHODS

This project aims to widen the breadth of knowledge available to those involved in informing wheelchair provision, analyze the impact of wheelchair fit measures on patient-reported outcomes, and explore the potential of new wheelchair fit measures as predictors of shoulder pain. This study was approved by the University of Wisconsin Institutional Review Board (19.A.257).

Participants

Forty manual wheelchair users (27 male, 13 female) were recruited for this study based on having sustained SCI/D – the most second common diagnosis in this study being spina bifida. Participants in this project were required to be older than the age of 18 and be more than a year past the onset of their medical condition. All participants were screened for eligibility and signed an informed consent prior to participation. Participants had an average age of 39.8 years ± 13.8 and an average years-since-injury/onset (YSI) of 22.3 years ± 14.6 years. The sample was split into two groups which were distinguished by when the diagnosis was received – either as a child (Pediatric-Onset) or an adult (Adult-Onset). SCI/D individuals had to be diagnosed with paraplegia, and it was required that participants use their manual wheelchair for at least 50% of their daily mobility. Participants also must not have had contractures that impaired upper limb function or mobility, any infections at the time, no recent (within the last year) orthopedic surgeries to the upper extremity, any traumatic brain injury, or any other neurological conditions.

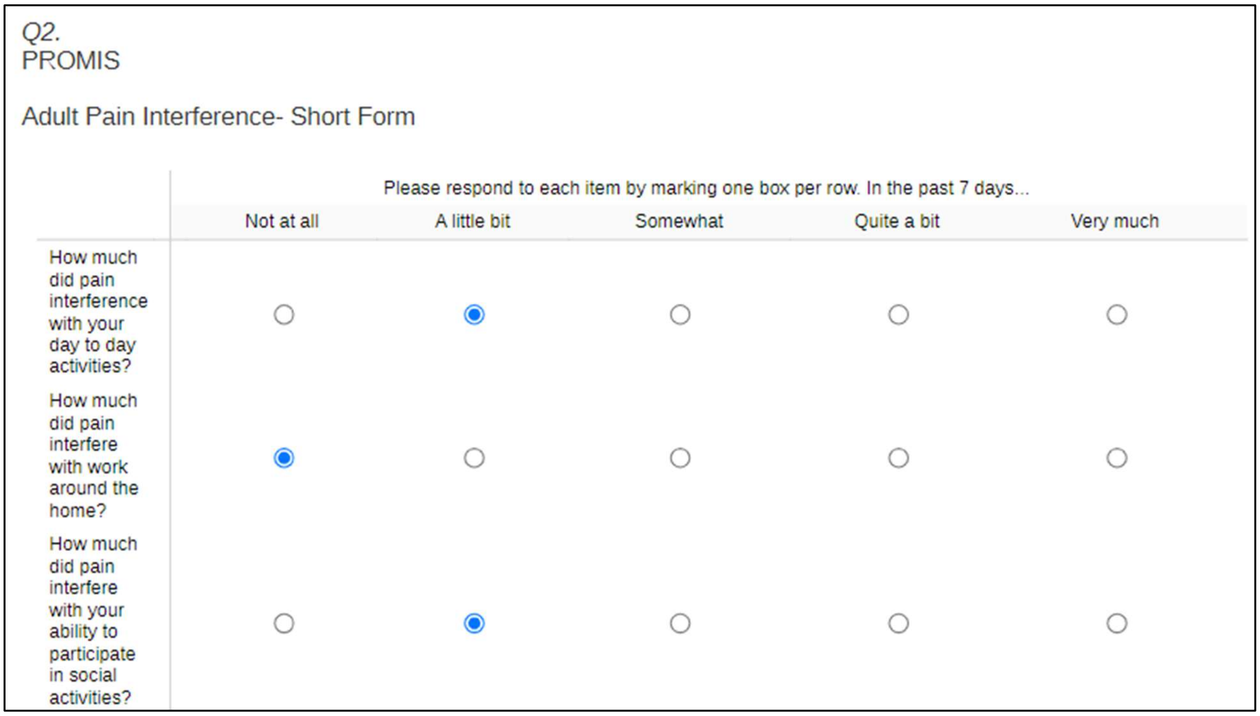
Participants were asked to fill out questionnaires relating to shoulder pain (WUSPI), pain interference (PROMIS pain interference), and independence (SCIM III). Measurements of wheelchairs were recorded, and the participants then propelled their manual wheelchairs at a self-selected pace across the laboratory. 3D motion capture was used to analyze the wheelchair fit variables and assess flexion-extension (sagittal plane) elbow angle at TDC.

Table 1: Subject Demographics. 40 adult participants with SCI/D were included. Participants 1-20 were adult-onset SCI/D and participants 21-40 were pediatric-onset. Biological sex, age, height, weight and year since injury were collected. Data about diagnosis and injury level were also recorded. SmartWheel side during propulsion and self-reported exercise were also included

Subject Demographics											
	ID	Sex	Age (years)	Height (cm)	Weight (kg)	Years Since Injury (YSI)	Diagnosis	Injury Level	ASIA Score	SmartWheel Side	Exercise
Adult-Onset	1	M	50.43	185.42	72.57	18.5	SCI	T12	B	N/A	Yes
	2	M	51.36	205.7	95.25	28.47	SCI	T10/T11	C	R	Yes
	3	M	49.56	190.5	65.77	29.94	SCI	C6/C7	B	L	Yes
	4	M	45.11	175.26	83.92	10.58	SCI	C6-C7	B	R	No
	5	M	54.03	157	46.70	22.67	SCI	T7/T8	A	R	Yes
	6	M	36.52	177.8	60.00	15.16	SCI	C6	A	R	Yes
	7	F	39.12	163	54.00	20.24	SCI	C6/C7	A	R	Yes
	8	M	55.18	182.88	59.00	35.27	SCI	T6	A	L	Yes
	9	M	43.03	189	82.00	11.32	SCI	T3	A	R	Yes
	10	M	65.27	178	77.30	40.37	SCI	C4/C5	B	R	Yes
	11	M	42.18	183	72.00	23.8	SCI	T4	A	R	Yes
	12	M	26.34	175	60.50	5.31	SCI	T10	A	R	No
	13	M	56.15	170.2	97.70	15.31	SCI	T4	B	R	No
	14	M	41.11	182.88	104.55	9.6	SCI	T12/L1	A	R	No
	15	F	67.56	157.48	51.36	29.72	SCI	C6	D	R	Yes
	16	M	25.2	182.88	81.65	1.72	SCI	T6	B	R	Yes
	17	M	30.01	180.34	77.11	21.6	SCI	T3/T4	A	R	Yes
	18	F	51.56	157.5	102.06	4.27	SC Stroke	T4	D	R	Yes
	19	M	47.59	187.96	99.79	6.39	SCI	C7	B	L	Yes
	20	M	25.45	175.25	63.05	1.51	SCI	T9	C	L	Yes
Pediatric-Onset	21	M	60.51	172.72	71.67	46.1	SCI	T11/T12	A	R	Yes
	22	M	51.95	162.56	90.72	51.95	SB	L4	B	L	Yes
	23	M	39.79	177.8	103.42	25.18	SCI	T6	A	R	Yes
	24	M	31.85	170.18	147.73	31.85	SB	L3	B	R	Yes
	25	F	51.19	142.24	81.82	51.19	SB	L3	C	R	No
	26	F	20.82	142.24	77.11	20.82	SB	L3/L4	A	R	Yes
	27	M	57.22	167	68.00	57.22	SB	L3	A	R	No
	28	F	32.43	160	52.20	21.7	TM	L2/L3	A	R	Yes
	29	F	25.62	170.18	49.90	14	SCI	T10	A	R	No
	30	F	46.32	155.94	81.64	46.3	SB	L3	C	R	No
	31	M	32.05	160.2	72.57	23.05	SB	L1	A	L	Yes
	32	F	20.37	137.16	63.50	20.37	SB	L3, L5/S1	B	R	No
	33	M	32.21	172.72	92.99	15.33	SCI	T11	A	R	No
	34	M	47.98	175.25	79.37	32.24	SCI	T6	A	L	No
	35	F	32.39	160	104.32	31.62	SCI	T10	C	L	Yes
	36	F	20.97	157.48	63.50	4.93	SCI	T5	A	R	Yes
	37	M	21.46	167.6	66.60	18.74	SCI	L3	D	R	Yes
	38	F	21.28	162.2	63.50	16.92	SCI	T1	A	R	No
	39	M	20.94	179.07	70.45	5.81	SCI	C6	D	L	Yes
	40	F	23.07	162.56	81.65	5.8	SCI	T2	A	R	No
Averages			Age (years)	Height (cm)	Weight (kg)	YSI (years)					
Group Avg. (std. dev.)			39.83 (±13.81)	170.30 (±14.11)	77.22 (±19.78)	22.32 (±14.57)					
Adult-Adult Avg. (std. dev.)			45.14 (±12.25)	177.85 (±12.34)	75.31 (±17.86)	17.59 (±11.39)					
Adult-Ped Avg (std. dev.)			34.52 (±13.50)	162.76 (±11.68)	79.13 (±21.82)	27.06 (±16.09)					

Data Collection Procedure

After being consented to participate in the study, participants were administered the patient-reported outcomes questionnaire via Qualtrics software tool. The outcomes that were included in the questionnaire were the Wheelchair User's Shoulder Pain Index (WUSPI), the Spinal Cord Independence Measure Version 3 (SCIM III), and the Patient-Reported Outcomes Measurement Information System (PROMIS) Pain Interference Short Form 8a. A portion of the SCIM III which contained more sensitive questions was administered by physicians. Qualtrics-administered survey responses were downloaded in pdf format and physician-administered responses were scanned in (Figure 2). After patient-reported outcomes were recorded, further subject information was gathered. This included a confirmation of participant eligibility, subject anthropomorphic measurements, and assistive device history.



Q2.
PROMIS

Adult Pain Interference- Short Form

Please respond to each item by marking one box per row. In the past 7 days...

	Not at all	A little bit	Somewhat	Quite a bit	Very much
How much did pain interference with your day to day activities?	○	●	○	○	○
How much did pain interfere with work around the home?	●	○	○	○	○
How much did pain interfere with your ability to participate in social activities?	○	●	○	○	○

Figure 2: An example of the Qualtrics administered PROMIS survey for adult pain interference.

32 retroreflective markers were then placed on the participant using an upper extremity marker set developed by Schnorenberg et al. (2014). These markers were placed on bony landmarks and other strategic positions on the upper extremities and torso to reconstruct a 3D model of each participant. A marker set and MATLAB script were developed by Frank (2021) and further refined to quantify measurements of the wheelchair setup using the motion capture

acquisition. Markers were placed on the seat, the seat frame, wheel axle hubs, and backrest (Figure 3).

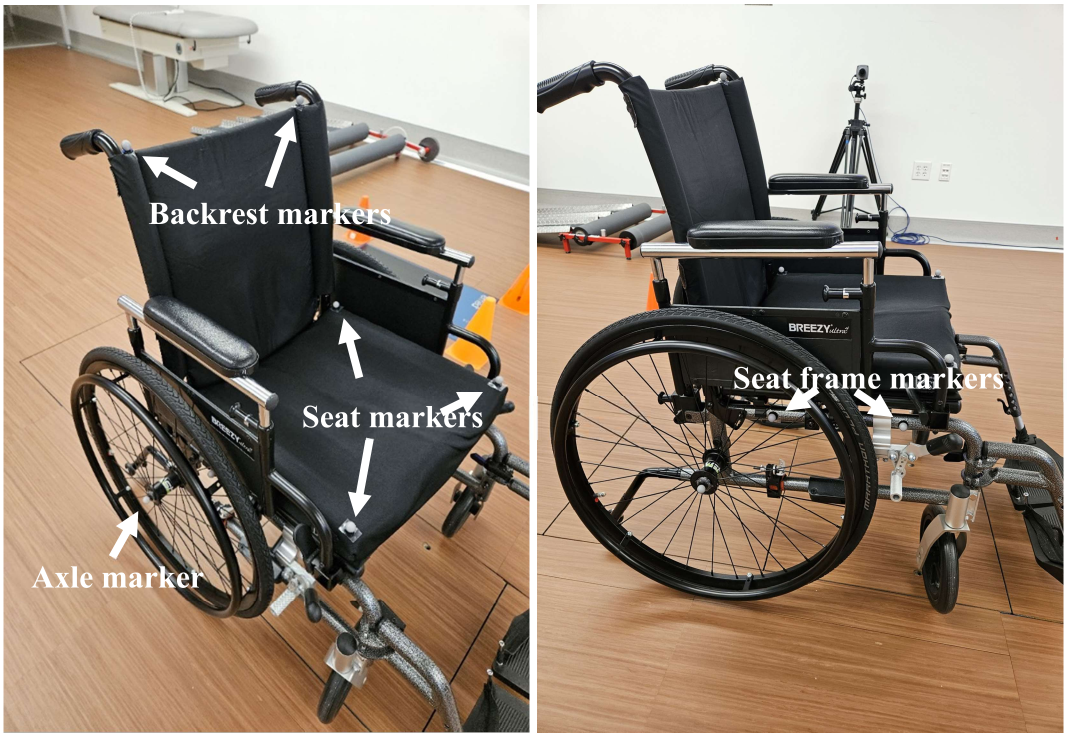


Figure 3: Ten wheelchair markers were used to calculate wheelchair fit measures. The markers are on the backrest, axles, seat, and seat frame.

A 15-camera Vicon Nexus (Vicon Motion Systems Ltd. Oxford, UK) system was used to capture two static images. One of the participant's wheelchair and another of the participant in the wheelchair with their hands placed at top-dead-center (TDC) of their wheel. Top-dead-center is defined as the location on the top of the hand-rim at the very center of the wheel, above the rear axle. The 3D position data of each marker was averaged over the duration of the static trials. Then, the wheelchair fit measures and elbow kinematics were extrapolated from the data set with the use of MATLAB scripts (2023a; The Mathworks Inc., Natick, MA). The following are brief descriptions of the wheelchair fit variables, why they were chosen, and how they were calculated.

Wheelchair Fit Measures:

Horizontal Axle Position (HAP) **–** Horizontal axle position has an impact on MWUs kinematics and kinetics that has been studied previously (Boninger, 2000, 2005; Frank, 2021).. Boninger et al. (2000, 2005) looked at the effects of varying axle positions on propulsion mechanics. It was found that as horizontal axle position moved more anteriorly, push angle increased, which in turn slowed cadence and lead to a "decrease in rate of rise of the resultant force". Horizontal axle position was determined by subtracting the position of the middle point of the rear axle from the middle point between the acromion markers in the sagittal plane – so, a more negative HAP indicates a forward axle position relative to the acromion and a more positive HAP indicates a more posterior position.

Vertical Axle Position (VAP) **–** Vertical axle position also impacts kinetics and kinematics for MWUs, albeit slightly differently than HAP. Vertical axle position influences the elbow and GH joint angles at top-dead center and throughout propulsions (Cowen, 2009; Boninger, 2000). It was found that increasing VAP will increase elbow angle at TDC, while decreasing VAP will decrease elbow angle at TDC. Boninger et al. also determined that optimal

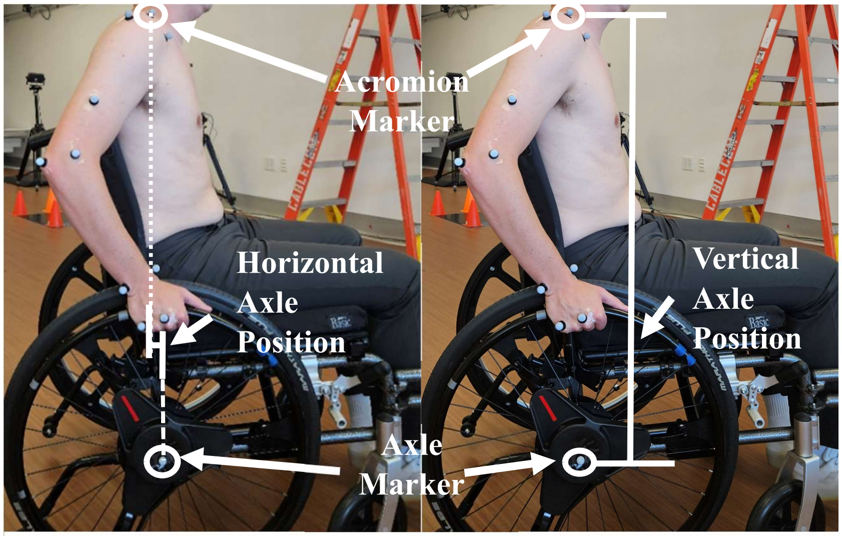


Figure 4: Axle position. This figure depicts how horizontal and vertical axle position were measured using markers on the axles and acromion processes.

elbow angle at TDC is between 100-120°. However, no comparisons between optimal elbow angle and patient-reported outcomes have been made previously – which is why this measure was included in this project.

Backrest Height (BH) **–** Backrest height is another variable of wheelchair fit that can affect kinematics and kinetics. This variable is related to trunk stability and posture and is heavily influenced by level of injury (Yang 2012). Additionally, Boninger et al. (2005) found that a lower backrest height can increase range of motion during propulsion, which can lower cadence.

Seat Width (SW) **–** Seat width is a WC fit variable that can affect comfort and propulsion mechanics. If a seat is too narrow, it can cause pressure on the legs due to the proximity of the armrests – potentially leading to ulcers. Conversely, if a seat is too wide, this can cause too much shoulder abduction and potentially lead to injury (RESNA, 2012).

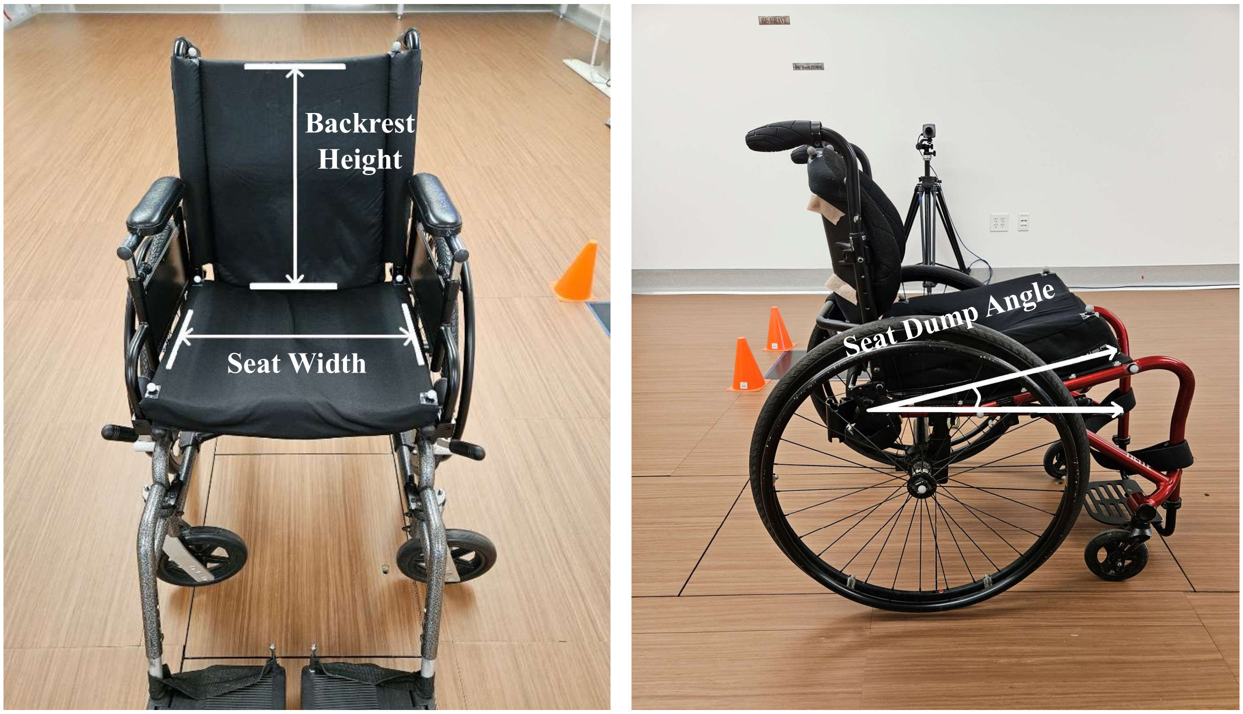


Figure 5: (Left) A front-on view of a wheelchair showing the backrest height and seat width wheelchair variables. (Right) A side-on view of the seat dump angle wheelchair variable.

Seat Dump Angle (SDA) **–** Seat dump angle can directly affect the orientation of the pelvis. Due to this interaction, SDA is important for MWUs because the positioning of the pelvis influences comfort and trunk control. Cloud et al. (2017) found that increasing SDA from 0° to 14° decreased lordosis throughout the propulsion trials. However, this study also noted that increasing SDA past what is necessary can lead to increased difficulty in transferring.

Top Dead Center (TDC) – Static images were taken of the participants in their wheelchairs to gather 2D and 3D data on their elbow angles while their hands were on top of their wheelchair wheel. Then participants were categorized into optimal and non-optimal elbow angle groups if their elbow angles were 100-120 degrees using Boninger's (2005) methodology, and 60-80 degrees of flexion-extension using Yang's (2012) criteria.

Figure 6: A wheelchair user with their hands at "top-dead-center" (TDC) of their wheelchair wheel

Kinetics

Propulsion kinetics were collected via the use of a SmartWheel™ instrumented wheelchair wheel. The SmartWheel™ is equipped with sensors that capture data on forces, moments, and speed during wheelchair propulsion. Specifically, propulsion cadence and peak resultant forces on the hand rim were collected. Cadence was recorded as pushes per second, while peak resultant forces on the hand rim were reported in Newtons (N). Only participants with high-quality, defined by the number of usable trials and perceived accuracy of the data collected, were included into the analysis.

Data Analysis

The statistical methods used in this project were conservative and did not assume normality in this data set. Non-parametric statistical analysis was chosen due to the ordinal nature of the data set, the robustness of the analysis (i.e. including outliers), and the small sample size. Spearman's rank order methods were used for correlational analyses. The Spearman's rank order outputs a Rho-value which can be categorized in various ways depending on the field. For the context of this project, Rho-values were categorized following this table:

Table 2: Spearman's Rho-values and their associated correlation descriptors

Spearman's Rho-Value	Correlation
0.00 to 0.20	Negligible
0.21 to 0.40	Weak
0.41 to 0.60	Moderate
0.61 to 0.80	Strong
0.81 to 1.00	Very Strong

The non-parametric test, Wilcoxon rank sum test, was used for assessing group differences in the data set. It is also known as the Mann-Whitney U test. This test solely outputs a p-value which indicates the likelihood that the differences between the two groups are statistically significant. Statistical significance for both group comparisons and correlations were determined by p-values <0.05.

RESULTS

Participants

Of the 40 participants included in this project, there were 27 males and 13 females. Participants had an average age of 39.83 ±13.81 years, an average height of 1.70 ±.14 m, and an average weight of 77.22 ±19.78 kg. As a group, the participants had an average time since their injury/diagnosis of 22.32 ±14.57 years. Adult and pediatric onset SCI/D averages can be seen at the bottom of Table 1 and in Appendix A.

In the adult-onset group, most of the diagnoses were SCI– with only 1 of the 20 in that group that had sustained a spinal cord stroke that led to paraplegia. For the pediatric-onset group, there were 11 participants that had sustained an SCI and 8 that had paraplegia due to spina bifida. There was 1 participant in the pediatric-onset group that was affected by paraplegia due to transverse myelitis. The level of injury in the whole sample ranged from C4 to L5/S1 and ASIA scores can be found in Table 1; analyses were not conducted using either metric.

Aim 1 – *Determining the relationship between wheelchair fit variables, self-reported pain, and other patient-reported outcomes*:

To determine the relationships between wheelchair fit and PRO, Spearman's methods were used to examine correlations. The wheelchair fit variables that were focused on for this aim were horizontal and vertical axle position (HAP and VAP), backrest height (BH), and seat dump angle (SDA). PC-WUSPI, PROMIS pain interference, and SCIM version III were the patient-reported outcomes of interest.

Horizontal Axle Position (HAP) – HAP seemed to differ significantly between the groups, with the adult-onset group having a more negative HAP on average [-1.74 (±5.58) cm] –

indicating a more forward axle position. On the other hand, the pediatric-onset group had a more positive HAP on average [1.68 (±7.55) cm] and indicated a more rearward axle position. This difference was not statistically significant, however. There was also no statistical evidence to support the case for a correlation between HAP and PC-WUSPI, PROMIS, or SCIM III.

Table 3: Spearman's correlation Rho and p-values for horizontal axle position versus PC-WUSPI, PROMIS, and SCIM III outcomes. Correlations were statistically significant if their p-value was <0.05.

	HAP (cm)	**PC-WUSPI**	**PROMIS**	**SCIM III**
w	-0.03 (±6.77)	24.83 (±26.62)	55.85 (±8.82)	61.88 (±12.18)
p-value		0.44	0.29	0.98
Rho		0.13	-0.17	0.00

Vertical Axle Position (VAP) – VAP did not differ significantly between the two groups, and this was confirmed by a Wilcoxon rank sum test. The adult-onset group had a mean VAP of 73.78 (±4.75) cm and the pediatric-onset group had a mean VAP of 71.15 (±4.51) cm. When VAP was correlated with PC-WUSPI and PROMIS pain interference, there was a statistically significant (p-value <0.05) weak correlation between them with a Rho-value of 0.39 and 0.40, respectively.

Table 4: Spearman's correlation Rho and p-values for vertical axle position versus PC-WUSPI, PROMIS, and SCIM III outcomes. Correlations were statistically significant if their p-value was <0.05.

	VAP (cm)	**PC-WUSPI**	**PROMIS**	**SCIM III**
Mean (std. dev.)	72.46 (±4.76)	24.83 (±26.62)	55.85 (±8.82)	61.88 (±12.18)
p-value		**0.01***	**0.01***	0.48
Rho		0.39	0.40	-0.11

Backrest Height (BH) – For backrest height, there was a high amount of variability relative to the average backrest height, 41.21 (±16.05) cm. There were no statistically significant differences in group means between the adult-onset and pediatric-onset groups. There was also no statistically significant correlation between backrest height and any of the three patient-reported outcomes that were analyzed.

Table 5: Spearman's correlation Rho and p-values for backrest height versus PC-WUSPI, PROMIS, and SCIM III outcomes. Correlations were statistically significant if their p-value was <0.05.

	BH (cm)	PC-WUSPI	PROMIS	SCIM III
Mean (std. dev.)	41.21 (±16.05)	24.83 (±26.62)	55.85 (±8.82)	61.88 (±12.18)
p-value		0.33	0.85	0.31
Rho		-0.16	0.03	-0.16

Seat Dump Angle (SDA) – The SDA had an overall average of 7.59 (±3.19) degrees, with the adult-onset group having a non-statistically significant, larger SDA. In this sample, there were no statistically significant correlations between seat dump angle and any of the three patient-reported outcomes.

Table 6: Spearman's correlation Rho and p-values for seat dump angle (deg) versus PC-WUSPI, PROMIS, and SCIM III outcomes. Correlations were statistically significant if their p-value was <0.05.

	SDA (deg)	PC-WUSPI	PROMIS	SCIM III
Mean (std. dev.)	7.59 (±3.19)	24.83 (±26.62)	55.85 (±8.82)	61.88 (±12.18)
p-value		0.19	0.72	0.67
Rho		0.21	0.06	0.07

Aim 2 – ***To determine the relationships between wheelchair fit variables and flexion-extension elbow angle at top dead center:***

To determine the relationships between wheelchair fit variables and elbow angle, Spearman's methods were used to examine correlations. The wheelchair fit variables that were focused on for this aim were horizontal and vertical axle position and seat width. This angle was reported as a 3D sagittal plane elbow angle, or elbow flexion-extension angle that was calculated using the upper extremity model created by Schnorenberg et al. (2014). It was also computed as a 2D sagittal elbow angle using similar methodology to Frank (2021) and Boninger et al. (2000).

2D Elbow Angle – The calculated 2D elbow angle had an average of 97.63 (±11.02) degrees in the sagittal plane. This average falls outside the "optimal" range of 100-120 degrees for 2D sagittal elbow angle at TDC (Boninger, 2000). A total of 16 participants out of 40 fell within the optimal, recommended range for this metric. There were no statistically significant correlations found between 2D elbow angle and the WC fit variables.

Table 7: Spearman's correlation Rho and p-values for 2D elbow angle (deg) versus seat width (cm), vertical axle position (cm), and horizontal axle positions (cm). Correlations were statistically significant if their p-value was <0.05.

	2D Elbow Angle (deg)	Seat Width	VAP (cm)	HAP (cm)
Mean	97.63 (±11.02)	35.87 (±7.92)	72.46 (±4.76)	-0.03 (±6.77)
p-value		0.20	0.09	0.09
Rho		-0.21	-0.28	0.28

3D Sagittal Elbow Angle – The calculated 3D sagittal elbow angle had an average of 82.45 (±10.98) degrees in the sagittal plan. This average falls outside the optimal elbow flexion range of 60-80 degrees for 3D sagittal elbow angle at TDC (Ryu et al., 2017). A total of 17 out of

40 participants fell within the optimal range for this metric. There were no statistically significant correlations found between 3D elbow angle and seat width or horizontal axle position. There was, however, a statistically significant negative correlation between vertical axle position and 3D flexion-extension angle.

Table 8: Spearman's correlation Rho and p-values for 3D sagittal elbow angle (deg) versus seat width (cm), vertical axle position (cm), and horizontal axle positions (cm). Correlations were statistically significant if their p-value was <0.05.

	3D Sag. Elbow Angle (deg)	Seat Width (cm)	VAP (cm)	HAP (cm)
Mean	82.45 (±10.98)	35.87 (±7.92)	72.46 (±4.76)	-0.03 (±6.77)
p-value		0.16	**0.04***	0.07
Rho		-0.22	-0.33	0.29

Sub-Aim 2a – *To determine group differences between participants with optimal versus non-optimal elbow positions at top dead center:*

To determine the groups differences in wheelchair fit and PROs between those who had optimal and those who had non-optimal elbow angles as defined by Boninger and Ryu for both methodology, the Wilcoxon rank sum method was used. This method was used because of the non-parametric and imbalanced nature of the two groups.

Table 9: Wilcoxon rank sum p-values for between optimal and non-optimal elbow angle groups to determine differences in group means for seat width, vertical axle position, horizontal axle position, PC-WUSPI, PROMIS, SCIM III, cadence, and peak resultant force. Differences were statistically significant if their p-value was <0.05.

	Seat Width (cm)	**VAP (cm)**	**HAP (cm)**
Optimal	36.99 (±5.26)	73.76 (±4.53)	3.42 (±4.88)
Non-optimal	35.27 (±9.08)	71.77 (±4.82)	-1.89 (±6.99)
p-value	0.64	0.20	**0.01***
	PC-WUSPI	**PROMIS**	**SCIM III**
Optimal	30.6 (±37.12)	57.49 (±10.5)	59.21 (±14)
Non-optimal	37.12 (±21.73)	10.5 (±54.98)	14 (±63.31)
p-value	0.79	0.6	0.42
		Cadence (/s)	**Peak Resultant Force**
Optimal		0.95 (± 0.34)	62.06 (± 20.95)
Non-optimal		0.97 (± 0.25)	57.72 (± 28.14)
p-value		1.00	0.27

Aim 3 – *To determine the relationships between wheelchair fit variables and propulsion cadence and peak resultant force:*

To determine the relationships between wheelchair fit variables and propulsion cadence, Spearman's methods were used to examine correlations. The wheelchair fit variables that were investigated were horizontal axle position and backrest height. Cadence was reported as push frequency or pushes per second.

Backrest Height (BH) – Backrest height did not correlate significantly to either cadence or peak resultant force during propulsion.

Table 10: Spearman's correlation Rho and p-values for backrest height (cm) versus mean resultant force (N) and cadence (/s). Correlations were statistically significant if their p-value was <0.05.

	Backrest Height (cm)	Resultant Force (N)	Cadence (/s)
Mean (std. dev.)	41.21 (±16.05)	61.13 (±25.15)	0.98 (±0.25)
p-value		0.75	0.85
Rho		-0.06	-0.03

Horizontal Axle Position (HAP) – Horizontal Axle position did not correlate significantly to either cadence or resultant force during propulsion.

Table 11: Spearman's correlation Rho and p-values for horizontal axle position (cm) versus mean resultant force (N) and cadence (/s). Correlations were statistically significant if their p-value was <0.05.

	Horizontal Axle Position (cm)	Resultant Force (N)	Cadence (/s)
Mean	-0.03 (±6.77)	61.13 (±25.15)	0.98 (±0.25)
p-value		0.74	0.21
Rho		0.06	-0.22

Vertical Axle Position (HAP) – Vertical Axle position did not correlate significantly to either cadence or resultant force during propulsion.

Table 12:Spearman's correlation Rho and p-values for vertical axle position (cm) versus mean resultant force (N) and cadence (/s). Correlations were statistically significant if their p-value was <0.05.

	Vertical Axle Position (cm)	Resultant Force (N)	Cadence (/s)
Mean	-0.03 (±6.77)	61.13 (±25.15)	0.98 (±0.25)
p-value		0.10	0.18
Rho		0.28	0.22

Aim 4 – *To determine group differences in patient-reported outcomes, wheelchair fit variables, and kinetics between adults in adult-onset and pediatric-onset groups:*

To determine the groups differences within wheelchair fit, PROs, and kinetics, Wilcoxon rank sum method was used due to the non-parametric and conservative nature of the test. The wheelchair fit variables that were focused on for this aim were horizontal and vertical axle position (HAP and VAP), backrest height (BH), and seat dump angle (SDA). PC- WUSPI, PROMIS, and SCIM version III were the patient-reported outcomes of interest. The propulsion kinematics and kinetics that were compared were cadence (pushes/second) and resultant force (N), respectively.

Patient-Reported Outcomes (PROs) – PC-WUSPI and SCIM III scores did not differ significantly between the groups using the Wilcoxon rank sum method. PROMIS pain interference scores did differ significantly with a Wilcoxon rank sum p-value of 0.05.

Table 13: Wilcoxon rank sum p-values for between adult-onset and pediatric-onset groups to determine differences in group means for PC-WUSPI, PROMIS, and SCIM III. Differences were statistically significant if their p-value was <0.05.

	PC-WUSPI	**PROMIS**	**SCIM III**
Adult-Onset Mean (std. dev.)	24.45 (±19.57)	58.37 (±8.28)	62.65 (±10.47)
Pediatric-Onset Mean (std. dev.)	25.22 (±32.74)	53.34 (±8.84)	61.10 (±13.91)
p-value	0.44	***0.05**	0.99

Wheelchair Fit Variables – There was no significant difference in wheelchair fit variables between adult-onset and pediatric-onset groups using Wilcoxon rank sum testing.

Table 14: Wilcoxon rank sum p-values for between adult-onset and pediatric-onset groups to determine group differences in horizontal axle position, vertical axle position, backrest height, and seat dump angle. Differences were statistically significant if their p-value was <0.05.

	HAP (cm)	**VAP (cm)**	**BH (cm)**	**SDA (deg)**
Adult-Onset Mean (std. dev.)	-1.74 (±5.58)	73.78 (±4.75)	39.28 (±14.14)	8.55 (±3.33)
Pediatric-Onset Mean (std. dev.)	1.68 (±7.55)	71.15 (±4.51)	43.14 (±17.91)	6.65 (±2.81)
p-value	0.06	0.11	0.58	0.1

Kinematics and Kinetics (Cadence and Peak Resultant Force) – There was no significant difference in dynamics between adult-onset and pediatric-onset groups using Wilcoxon rank sum testing.

Table 15: Wilcoxon rank sum p-values for between Adult-adult onset and Adult-pediatric onset groups to determine group differences in cadence (/s) and resultant forces (N). Differences were statistically significant if their p-value was <0.05.

	Cadence (/s)	**Peak Resultant Force (N)**
Adult-Onset Mean (std. dev.)	1.07 (±0.30)	52.30 (±18.20)
Pediatric-Onset Mean (std. dev.)	0.86 (±0.22)	66.05 (±29.73)
p-value	0.12	0.07

Aim 5 – *To perform an exploratory analysis on torso height to wheel size ratio and shoulder width to seat width ratio as a predictors of shoulder pain, pain interference, and independence:*

To explore these two ratios as predictors of shoulder pain, pain interference, and independence, Spearman's methods were used to examine if there was any correlation between the variables. Torso-height to wheel-size ratio (THWS Ratio) was calculated by dividing the calculated torso height by the measured wheel size. Similarly, the shoulder-width to seat-width ratio (SWSW Ratio) was calculated by dividing the calculated shoulder-width by the calculated seat-width.

Torso-height to wheel-size ratio (THWS Ratio) – There was no statistically significant correlation between the exploratory measure and PC-WUSPI or PROMIS Scores using Spearman's methods. There was a statistically significant negative correlation (p-value = 0.04, Rho = -0.33) between the THWS Ratio and SCIM III.

Table 16: Spearman's correlation Rho and p-values for the exploratory measure 'torso-height to wheel-size ratio' and PC-WUSPI, PROMIS, and SCIM III. Correlations were statistically significant if their p-value was <0.05.

	THWS Ratio	**PC-WUSPI**	**PROMIS**	**SCIM III**
Mean	1.07 (±0.15)	24.83 (±26.62)	55.85 (±8.82)	61.88 (±12.18)
p-value		0.81	0.61	***0.04**
Rho		0.04	-0.08	-0.33

Shoulder-width to seat-width ratio (SWSW Ratio) – There was no statistically significant correlation between this exploratory measure and PC-WUSPI or PROMIS Scores using Spearman's methods. There was a statistically significant positive correlation (p-value = 0.03, Rho = 0.34) between the SWSW Ratio and SCIM III.

Table 17: Spearman's correlation Rho and p-values for the exploratory measure 'shoulder-width to seat-width ratio' and PC-WUSPI, PROMIS, and SCIM III. Correlations were statistically significant if their p-value was <0.05.

	SWSW Ratio	**PC-WUSPI**	**PROMIS**	**SCIM III**
Mean	1.00 (±0.53)	24.83 (±26.62)	55.85 (±8.82)	61.88 (±12.18)
p-value		0.41	0.3	***0.03**
Rho		-0.13	-0.17	0.34

DISCUSSION

Introduction

The purpose of this project was to build upon existing literature relating to WC fit, PROs, and kinematics and kinetics of wheelchair use, with the focus being on a user-centered approach and personalization of the wheelchair. The intent of the project was to add to the existing knowledge base that is drawn upon by seating professionals and other therapeutic specialists to make wheelchair fit recommendations and to aid in the overall prescription of these assistive devices. The project adds to existing literature via several aims.

Aim 1 focused on determining the relationship between wheelchair fit variables and self-reported pain and independence. It was hypothesized that certain fit variables significantly influence pain levels. Aim 2 examined the relationships between wheelchair fit variables, such as seat width and axle positions, and the sagittal plane elbow angle at the top dead center. The hypothesis was that optimal positioning contributes to less risky joint angles. Aim 2 also included a sub-aim which examined group differences between those participants whose elbow angles were "optimal" vs. those whose were "non-optimal". The 3rd aim investigated the relationships between wheelchair fit, cadence, and resultant force, with an emphasis on how backrest height and axle position impacts propulsion mechanics and injury risks. Aim 4 aimed to identify differences in patient-reported outcomes, wheelchair fit variables, and kinetics between adult-onset and pediatric-onset groups. This aim explored the impact of age at onset on rehabilitation outcomes. Lastly, Aim 5 explored the potential predictive value of torso height to wheel size ratio and shoulder width to seat width ratio for pain and independence, providing insights into potential new metrics for wheelchair fit optimization.

Aim 1

The relationship that was investigated for Aim 1 was between various wheelchair fit measures and several PROs. Frank et al. (2011) found in their study of powered wheelchair users and their pain experience that about 59% of their sample attributed their pain to their seating. For this project, Spearman's correlational analysis was used to examine the nature of the association between each WC fit variable and the three PROs of interest. Of the four WC fit metrics, only one, vertical axle position (VAP), correlated significantly with any of the PROs. Specifically, a weak correlation was observed between VAP and both PC-WUSPI (p-value ≤ 0.01, Rho = 0.39) and PROMIS (p-value ≤ 0.01, Rho = 0.40). Although there is limited literature to compare this finding to, Boninger et. al. (2000) found that HAP impacts propulsion mechanics in the shoulder, particularly the length of stroke and cadence. It was expected that this relationship would be reflected in the current study because higher cadence can lead to overuse injuries, but HAP alone did not appear to drive pain or pain interference in this sample. This suggests a potential interaction effect between horizontal and vertical axle positions, indicating that neither variable should be considered in isolation.

Another interesting finding in this sample of wheelchair users was the substantial variability in backrest height (average = 41.21 ± 16.05 cm) and the lack of correlation between backrest height and PROs. Backrest heights varied from 18.5 cm to 74.5 cm, likely due to differences in level of injury and trunk control. The absence of a significant correlation between backrest height and pain was surprising, considering that Yang et al. (2012) found that a lower backrest could reduce propulsion cadence, theoretically protecting against overuse injury. The high variability in backrest height is interesting, but not unexpected, due to the relationship between that backrest height and level of injury and trunk control. Further research should explore the relationship between level of injury, ASIA score, and backrest height.

Aim 2

In Aim 2, the relationship of interest was that between wheelchair fit and elbow angle at "top dead center" (TDC). The elbow angle at TDC was calculated using 2D methodology, like in Boninger's work (2000), and 3D methods developed by Schnorenberg et al. (2014). Again, Spearman's methods were used to determine the relationships between the WC fit variables of interest and elbow angle. 2D elbow angle did not correlate significantly with any of the WC fit metrics, but it's possible that with a larger sample size that it would have when considering the p-values associated with VAP and HAP (both p-value = 0.09). On the other hand, 3D sagittal elbow angle was found to have a weak negative correlation to VAP (p-value = 0.04, Rho = -0.33). It appears this correlation would have also potentially been found with respect to HAP (p-value = 0.07) in a larger sample size and it further implies an interaction effect between VAP and HAP. These findings align with many of the studies done on axle positioning and elbow angle (Boninger et. al., 2000; Cowan et. al., 2009; Lafta et. al., 2018).

For sub-aim 2a, using 100-120 degrees for 2D methodology and 60-80 degrees for 3D sagittal plane elbow angle methodology, the participants were categorized as optimal if they fell into *both* ranges at TDC – otherwise they were considered "non-optimal". The goal of this aim was to discern if there were differences between the optimal and non-optimal groups in terms of certain WC fit variables, PROs, and dynamics. Overall, there were 14 of the 40 individuals who were considered in "optimal" positions at TDC, with 5 more being "optimal" in one metric but not the other. There were no statistically significant group differences in PC-WUSPI, PROMIS, or SCIM III scores. There were also no statistically significant differences in cadence or peak resultant force on the handrim. Similarly, for seat width and vertical axle positions, there were also no statistically significant differences between the groups. However, for horizontal axle position there was a statistically significant difference between groups (p-value = 0.01). The “optimal” group had an average HAP of 3.42 (±4.88) cm, meaning that the “optimal” group had an average HAP that was more posteriorly placed. This is in contrast to Boninger’s and others work which shows a more forward or anteriorly placed axle position leads to optimality in elbow angle at TDC. It is believed that this is indicative of an interaction between VAP and HAP and further supports the need to assess these variables together.

Aim 3 – Backrest height and HAP vs Dynamics

For Aim 3, the relationship of interest was that between backrest height, HAP and cadence and peak resultant force from the hand rim. It was hypothesized that there would be a relationship found between the wheelchair fit metrics and the kinetic measures. Yang et. al. (2012) found that using a backrest height lower than 40.6 cm allowed more range of motion, lowered cadence, and increase push angle. The sample in the current study had an average backrest height of 41.21 (±16.05) cm. When analyzing the effect of backrest height on cadence and resultant force during propulsion, there was no statistically significant correlation found between the variables in this sample. It is possible this is due to the method of analysis or even the range of the level of injury of the participants in the study, as there was a larger range of level of injury in this study compared to Yang et. al.

The horizontal axle position of WC fit is known to similarly influence cadence and resultant force. Boninger et. al. (2005) found that individuals who had their axles positioned more anteriorly had a lower cadence and a decrease in resultant force. In this study, no statistically significant relationship was found between horizontal axle position and cadence or resultant force.

Aim 4 – Group differences between participants with adult-onset and pediatric-onset SCI/D

Aim 4 of this study was to assess the differences in PROs, WC fit, and kinetics between the two onset groups: adult and pediatric-onset SCI/D. It is theorized by others that individuals that have early onset SCI/D have better outcomes, especially independence measures, than individuals with adult-onset SCI (Anderson et. al., 2006; Slavens et. al., 2015). This current study hypothesized that there would be group differences in PROs, WC fit, and dynamics.

When the analysis was performed on the group differences in PROs, only PROMIS scores differed with statistical significance (p-value = 0.05) while PC-WUSPI and SCIM III did not. Adults in the adult-onset group had an average PROMIS pain interference score of 58.37 (±8.28), while adults with pediatric-onset SCI/D had an average score of 53.34 (±8.84). PROMIS, in this case, is specifically focused on pain interference. In this sample, it seems as though the pediatriconset group was experiencing less pain interference compared to those with adult-onset SCI/D. This result is indicative of some sort of protective effect due to pediatric onset, but it is unclear what that protective factor is specifically.

This study hypothesized that there would be differences in wheelchair setup between onset groups. This was theorized because of the differences between the groups in their duration using a wheelchair. In other words, it was thought that having spent more time in their manual wheelchair, the pediatric-onset group would have tuned their setup to be more ideal for them. When looking at the rank sum analysis, there was no statistically significant difference between the groups in their WC fit. However, there were multiple WC fit variables that were close to being statistically significant. HAP, VAP, and SDA all had relatively low p-values (0.06, 0.11, and 0.1 respectively). It is possible that these would have been significant had there been a larger sample size or adjustment in significance level.

Lastly for this aim, group differences between kinetics were also examined. It was hypothesized that there would be differences in cadence and resultant force between the onset groups. The adult-onset group had an average cadence of 1.07 (±0.30) pushes/second, while the pediatric-onset group had an average cadence of 0.86 (±0.22) pushes/second. Although the adult-onset group has a higher cadence, this could be counteracted by lower resultant force compared to the pediatric-onset group. The adult-onset group had an average resultant force of 52.30 (±18.20) N, while the pediatric-onset group had a higher average resultant force of 66.05 (±29.73) N. However, there were no statistically significant differences found, with the Wilcoxon rank sum p-values for cadence and resultant force being 0.12 and 0.07 respectfully. Again, it is possible that these differences would have in fact been statistically significant with a larger sample size, a less conservative p-value, or even a more robust analysis. Future studies should focus on the interaction between cadence and resultant force between these onset groups and to establish a link between these metrics and WC fit variables.

Aim 5 – Exploratory analysis of THWS ratio and SWSW ratio

The last aim in this thesis was an exploratory Aim 5 that intended to analyze two ratios between anthropometric measures and WC fit measures as potential alternative measures. The idea was that these simpler measurements could be a replacement for more involved anthropometric and WC fit measures and as a predictor of PROs. Specifically, this thesis looked at the ratios of torso height to wheel size (THWS) and shoulder width to seat width (SWSW) in their relation to PC-WUSPI, PROMIS, and SCIM III scores. The average THWS ratio was 1.07 (±0.15) and the average SWSW ratio was 1.00 (±0.53). It's worth noting that there was a high amount of variability in the SWSW ratio metric. Spearman's correlation methods were used to determine if there were any relationships and PC-WUSPI and PROMIS showed no correlations with the exploratory measurements. SCIM III, an independence measure, correlated with the THWS and SWSW ratios with p-values of 0.04 and 0.03 respectively. The THWS ratio had a weak negative correlation to SCIM III score, and this could indicate that as an individual grows in relation to their wheel size, their ability to effectively interact with their environment, in other words their independence, diminishes. Conversely, the SWSW ratio had a weak positive correlation with SCIM III. This could indicate a relationship between healthier and more muscular shoulders lending themselves to being able to navigate their environments more independently. Although it doesn't seem as though these ratios correlate with pain or pain interference, there is merit in further studying measures like THWS and SWSW ratios or other similar proxy measures.

One thing to note when considering the impact of the exploratory analyses in this project is the high number of correlations and comparisons made. When running multiple statistical correlations, there is an increased risk of encountering type 1 errors – which occur when a false positive happens (Altman, 1991). The more statistical tests that are performed, there is a higher probability that at least one will have a significant result based purely by chance, even if there is no true correlation occurring. This is usually mitigated by corrections such as Bonferroni's, which adjusts the significance level to account for the number of comparisons made and reduces the likelihood of false positives (Zar, 2010). However, this was not performed in this project due to the exploratory nature of the thesis project and should be considered for future studies in this realm.

CHAPTER 3 – CONCLUSIONS

Future Research

For future studies on the topic of WC fit variables and the effects they can have on PROs, kinematics and kinetics, it would be useful for longitudinal data to be collected. The current study had a cross-sectional design and therefore collected the participant's PROs once. This only allows a limited perspective into their pain, pain interference, and independence and will not display their true outcomes over long periods of time. It would be beneficial to see how patient-reported outcomes evolve over longer periods of time, especially if a future study were to include changes to wheelchair fit being made. An intervention study could be beneficial to reveal longitudinal effects of changes in wheelchair fit.

Another aspect of this study that could be bolstered in future studies is the amount of wheelchair fit variables that are being collected and analyzed. One crucial missing piece in this study is the weight of the wheelchair. It is recommended by seating specialists that patients choose the most lightweight wheelchair possible. A future study could focus on the potential effects of wheelchair weight on PROs. Other wheelchair fit measures that could have an impact on PROs and merit further research are knee-to-seat depth, seat-to-lower leg support angle, lower leg support-to-foot support angle, and cushion type. A future study could utilize pressure sensors to analyze pressure gradients on the wheelchair seat. Cushion type has been known to greatly impact the user's perceived comfort in their chair. Along with additional wheelchair measurements, one could also expand on the anthropometric measures that are collected and utilized. For example, pelvic width would be useful to collect to compare to seat width and to analyze the impact this fit has on a metric such as shoulder abduction or comfort measures.

Expanding the PROs being explored to include a measure for comfort would also be beneficial to clinicians and seating specialists. There are several PROs and measures that would be suitable to explore in future studies as well. Survey data about tips and falls, at-home use of wheelchairs, and occupational uses of wheelchairs could also be useful in framing perceived outcomes relating to overall wheelchair use. Some specific measures that could be insightful are the Wheelchair Outcome Measure (WhOM), Functional Independence Measure (FIM), Psychosocial Impact of Assistive Devices Scale (PIADS) and the Wheelchair Skills Test (WST). These additional surveys and measures could provide a more well-rounded depiction of day-to-day wheelchair use and lead to a deeper understanding of the impacts of wheelchair use on several domains.

Lastly, future studies should utilize more robust statistical analysis methodology to coax out interaction effects between WC fit variables, like vertical and horizontal axle positions. A more robust analysis could be useful to control for factors such as level of injury, sex, years since injury, and other potential confounding variables. A multi-variate analysis, such as a multivariate analysis of variance (MANOVA), of WC fit variables could give a better understanding of the holistic impact of WC fit metrics on PROs and biomechanics. Along with a multivariate analysis, future studies should better control for confounding variables such as level of injury and ASIA score.

Conclusions

This thesis explored several domains of wheelchair use and the impact they can have on the health and well-being of individuals with SCI/D. Through an analysis of various biomechanical, functional, and WC fit variables associated with wheelchair use and set up, this research project highlights the multifaceted nature of mobility in a wheelchair. The personalization of the wheelchair can significantly improve life satisfaction, as well as reduce the risk of secondary health complications such as pressure sores and musculoskeletal pain. Another glaring conclusion from this thesis is the need to continue with the interdisciplinary approach to assessing wheelchair use.

To interpret the perceived outcomes of wheelchair users, several patient-reported outcomes and measures were administered and analyzed in this project. The surveys and assessment tools that were utilized in this thesis were the Wheelchair User's Shoulder Pain Index (WUSPI), Spinal Cord Independence Measure Version III (SCIM III), and the Patient-Reported Outcomes Measurement Information System (PROMIS) Pain Interference Short Form 8a. These tools helped to provide insights into the wheelchair user's pain, pain interference, and independence and gave a concrete interpretation of some abstract measures, such as pain interference or independence. For example, the WUSPI helps in identifying shoulder pain, which is obviously a significant issue for wheelchair users, and can provide insight into which activities are causing the user to experience pain. These assessments remain an indispensable set of tools for clinicians, researchers, seating specialists, and even policy makers who have the intention of enhancing the quality of care and support that wheelchair users receive.

A recurring theme throughout this thesis project is the need for continuing the practice of interdisciplinary collaboration and user-centered approach. Addressing the challenges faced by wheelchair users requires the multi-faceted expertise that engineers, healthcare professionals, ergonomists/seating professionals, and the users themselves all bring to the table. By continuing to foster collaboration across these disciplines, innovative solutions can be developed that are both practical in addressing the user's needs and technically sound. Additionally, involving wheelchair users in the setup process of the wheelchair prescription ensures that their voices and concerns are heard and that their needs are prioritized. This collaborative approach hopefully can lead to the development of wheelchair guidelines that are focused on functionality and enhancing the wheelchair user's experience with the chair and quality of life as well. This approach has the added benefit of empowering the individual through giving them a stake in the process of the development of an assistive device that they rely on daily, leading to a feeling of agency and ownership over their wheelchair.

In terms of wheelchair prescription, the results of this thesis indicate that seating professionals should consider the interactions between various wheelchair fit measures. Instead of focusing on singular variables like horizontal axle position, seat dump angle, or seat width, seating professionals and rehabilitation engineers should instead find settings that consider optimal positioning of factors that interact with one another. For example, instead of trying to optimize elbow flexion angle based solely off changing axle position, wheelchair prescription should seek to optimize elbow flexion based off HAP, VAP, seat dump angle and seat width in such a way that also fulfills the needs and comfort of the user. In other words, this research indicates that just moving HAP forward, as other studies indicate, may not be sufficient in a holistic approach to WC fit and optimizing the user's set up. Future research could focus on algorithms or machine learning that seek to optimize wheelchair fit based off input from the seating professional and wheelchair user.

Looking ahead, identified several other areas for future research and best practice techniques. One important area is longitudinal studies that are focused on the interactions between WC fit, PROs, and biomechanics. In general, more longitudinal studies are needed to understand and track the long-term outcomes of wheelchair use. A longitudinal study focused on WC fit and their impacts on PROs and biomechanics would provide a more in depth idea of which WC fit variables are most impactful on the outcomes of wheelchair users. These types of studies would be beneficial in informing superior wheelchairs that can adapt to the ever-changing needs of the user. Future studies could also expand on the library of surveys and assessment tools to either be more robust, like the Functional Independence Measure (FIM) or Psychosocial Impact of Assistive Devices Scale (PIADS), or focus specifically on wheelchair mobility such as the Wheelchair Outcome Measure (WhOM) or Wheelchair Skills Test (WST).

Lastly, more robust experimental design and statistical analysis could be used to try and discern the interactions between the various aspects of WC fit and PROs or biomechanics. It would be helpful to collect all wheelchair fit measures and other important anthropometric measurements and then be able to carry out analyses on those which are thought to affect the various domains of wheelchair use. Specifically, wheelchair weight was an important aspect of fit that was not collected in this study. Then, multi-variate statistical models could be carried out to get more accurate results that include the interactions between the variables, like horizontal axle and vertical axle position, that affect biomechanics and PROs.

In conclusion, this thesis calls for a holistic, multi-modal approach to wheelchair fit and guidelines, emphasizing the need for interdisciplinary collaboration and user-centered design. By addressing the physical, psychological, and social dimensions of wheelchair use, therapists and health professionals can better support individuals in achieving their fullest potential and leading fulfilling, independent lives. The journey towards better mobility for wheelchair users is ongoing and needs more longitudinal research to enhance the knowledge base on wheelchair use and develop impactful clinical guidelines for wheelchair fit. As technology advances and our understanding of the needs of wheelchair users deepens, we must continue to innovate and adapt. By fostering a society and rehabilitation services that value user-centered design, inclusivity, and accessibility, we can ensure that wheelchair mobility is not a barrier that is insurmountable.

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APPENDIX A – Tables

Subject Demographics

	ID	Sex	Age (years)	Height (cm)	Weight (kg)	Years Since Injury (YSI)	Diagnosis	Injury Level	ASIA Score	SmartWheel Side	Exercise
Adult-Onset	1	M	50.43	185.42	72.57	18.5	SCI	T12	B	N/A	Yes
	2	M	51.36	205.7	95.25	28.47	SCI	T10/T11	C	R	Yes
	3	M	49.56	190.5	65.77	29.94	SCI	C6/C7	B	L	Yes
	4	M	45.11	175.26	83.92	10.58	SCI	C6-C7	B	R	No
	5	M	54.03	157	46.70	22.67	SCI	T7/T8	A	R	Yes
	6	M	36.52	177.8	60.00	15.16	SCI	C6	A	R	Yes
	7	F	39.12	163	54.00	20.24	SCI	C6/C7	A	R	Yes
	8	M	55.18	182.88	59.00	35.27	SCI	T6	A	L	Yes
	9	M	43.03	189	82.00	11.32	SCI	T3	A	R	Yes
	10	M	65.27	178	77.30	40.37	SCI	C4/C5	B	R	Yes
	11	M	42.18	183	72.00	23.8	SCI	T4	A	R	Yes
	12	M	26.34	175	60.50	5.31	SCI	T10	A	R	No
	13	M	56.15	170.2	97.70	15.31	SCI	T4	B	R	No
	14	M	41.11	182.88	104.55	9.6	SCI	T12/L1	A	R	No
	15	F	67.56	157.48	51.36	29.72	SCI	C6	D	R	Yes
	16	M	25.2	182.88	81.65	1.72	SCI	T6	B	R	Yes
	17	M	30.01	180.34	77.11	21.6	SCI	T3/T4	A	R	Yes
	18	F	51.56	157.5	102.06	4.27	SC Stroke	T4	D	R	Yes
	19	M	47.59	187.96	99.79	6.39	SCI	C7	B	L	Yes
	20	M	25.45	175.25	63.05	1.51	SCI	T9	C	L	Yes
Pediatric-Onset	21	M	60.51	172.72	71.67	46.1	SCI	T11/T12	A	R	Yes
	22	M	51.95	162.56	90.72	51.95	SB	L4	B	L	Yes
	23	M	39.79	177.8	103.42	25.18	SCI	T6	A	R	Yes
	24	M	31.85	170.18	147.73	31.85	SB	L3	B	R	Yes
	25	F	51.19	142.24	81.82	51.19	SB	L3	C	R	No
	26	F	20.82	142.24	77.11	20.82	SB	L3/L4	A	R	Yes
	27	M	57.22	167	68.00	57.22	SB	L3	A	R	No
	28	F	32.43	160	52.20	21.7	TM	L2/L3	A	R	Yes
	29	F	25.62	170.18	49.90	14	SCI	T10	A	R	No
	30	F	46.32	155.94	81.64	46.3	SB	L3	C	R	No
	31	M	32.05	160.2	72.57	23.05	SB	L1	A	L	Yes
	32	F	20.37	137.16	63.50	20.37	SB	L3, L5/S1	B	R	No
	33	M	32.21	172.72	92.99	15.33	SCI	T11	A	R	No
	34	M	47.98	175.25	79.37	32.24	SCI	T6	A	L	No
	35	F	32.39	160	104.32	31.62	SCI	T10	C	L	Yes
	36	F	20.97	157.48	63.50	4.93	SCI	T5	A	R	Yes
	37	M	21.46	167.6	66.60	18.74	SCI	L3	D	R	Yes
	38	F	21.28	162.2	63.50	16.92	SCI	T1	A	R	No
	39	M	20.94	179.07	70.45	5.81	SCI	C6	D	L	Yes
	40	F	23.07	162.56	81.65	5.8	SCI	T2	A	R	No
Averages			Age (years)	Height (cm)	Weight (kg)	YSI (years)					
Group Avg. (std. dev.)			39.83 (±13.81)	170.30 (±14.11)	77.22 (±19.78)	22.32 (±14.57)					
Adult-Adult Avg. (std. dev.)			45.14 (±12.25)	177.85 (±12.34)	75.31 (±17.86)	17.59 (±11.39)					
Adult-Ped Avg (std. dev.)			34.52 (±13.50)	162.76 (±11.68)	79.13 (±21.82)	27.06 (±16.09)					

Wheelchair Fit Parameters

	Participant	HAP (cm)	VAP (cm)	Backrest Height (cm)	Seat Dump Angle (deg)	TH / Wheelsize	Shoulder Width / Seat Width
Adult- Adult Onset	1	-2.91	81.20	57.69	8.08	1.27	0.84
	2	6.72	79.26	24.87	10.33	1.02	0.76
	3	-9.01	73.56	50.74	13.00	1.46	0.92
	4	-5.76	74.92	37.72	6.26	1.23	0.76
	5	-6.32	65.45	24.59	9.33	0.90	0.76
	6	-0.06	71.13	59.31	7.75	1.12	0.85
	7	0.14	68.20	29.16	6.94	1.05	0.79
	8	3.19	74.29	20.64	12.57	0.94	1.16
	9	-4.94	80.19	38.68	7.70	0.89	0.78
	10	-15.49	71.60	24.39	4.30	1.05	1.02
	11	4.57	72.30	31.90	9.10	1.14	0.64
	12	5.23	77.65	30.69	6.68	1.09	1.07
	13	-4.66	77.67	27.79	6.43	0.94	0.78
	14	-1.18	75.83	29.08	12.69	1.16	1.01
	15	-4.83	64.44	44.97	4.49	0.95	0.71
	16	0.10	74.16	61.11	7.05	1.13	0.84
	17	5.70	71.15	53.54	10.17	1.08	1.22
	18	-0.03	70.41	66.07	4.83	1.11	0.75
	19	-6.38	80.32	39.18	5.97	0.87	0.95
	20	1.09	71.96	33.53	17.27	0.96	0.95
Adult- Pediatric Onset	21	1.31	74.74	18.51	8.87	0.93	1.02
	22	0.72	73.71	51.53	7.84	1.14	0.78
	23	-1.86	76.36	70.51	7.44	1.40	0.85
	24	-14.41	75.07	41.88	5.03	0.86	0.78
	25	12.06	72.39	22.18	10.80	1.13	0.88
	26	3.24	72.31	47.73	5.53	1.05	1.53
	27	-5.68	70.92	35.32	8.15	1.11	0.81
	28	4.45	69.76	54.09	10.13	1.28	0.99
	29	1.09	65.96	49.65	6.28	0.96	0.92
	30	14.00	64.26	32.94	1.16	0.84	0.57
	31	5.15	63.02	60.75	3.71	1.14	0.91
	32	3.24	68.15	43.76	1.82	1.05	0.69
	33	8.40	79.58	29.69	10.06	1.01	0.86
	34	5.86	75.53	21.63	6.76	0.93	0.96
	35	8.63	74.19	21.05	6.10	0.97	0.77
	36	8.23	68.07	69.45	3.56	1.40	1.01
	37	-8.32	70.07	30.17	6.54	0.87	0.89
	38	-2.71	68.15	60.88	6.17	1.21	2.23
	39	-12.37	75.42	26.54	11.38	0.98	1.30
	40	2.58	65.38	74.55	5.63	1.15	3.82
		HAP (cm)	VAP (cm)	Backrest Height (cm)	Seat Dump Angle (deg)	TH / Wheelsize	Shoulder Width / Seat Width
Group Avg. (std. dev.)		-0.03 (±6.77)	72.46 (±4.76)	41.21 (±16.05)	7.59 (±3.19)	1.07 (±0.15)	1.00 (±0.53)
A-A Avg. (std. dev.)		-1.74 (±5.58)	73.78 (±4.75)	39.28 (±14.14)	8.55 (±3.33)	1.07 (±0.15)	0.88 (±0.15)
A-P Avg (std. dev.)		1.68 (±7.55)	71.15 (±4.51)	43.14 (±17.91)	6.65 (±2.81)	1.07 (±0.16)	1.13 (±0.73)

Patient Reported Outcomes

	Participant	PC-WUSPI	PROMIS	SCIM III
Adult- Adult Onset	1	23.37	77.0	52
	2	69.11	61.6	67
	3	47.48	61.7	53
	4	44.64	59.9	54
	5	16.12	61.6	74
	6	15.59	55.9	47
	7	4.13	51.1	70
	8	5.82	40.7	76
	9	3.19	66.3	71
	10	16.03	52.4	52
	11	53.96	55.4	49
	12	51.00	64.7	69
	13	23.73	59.7	41
	14	24.15	64.4	72
	15	12.64	58.5	68
	16	1.08	40.7	70
	17	28.60	61.2	72
	18	0.77	56.9	64
	19	29.83	63.4	69
	20	17.78	54.3	63
Adult- Pediatric Onset	21	35.83	58.3	68
	22	65.99	62.7	30
	23	39.86	58.3	49
	24	28.57	58.9	63
	25	5.48	40.7	45
	26	0.51	40.7	73
	27	20.62	55.9	44
	28	4.07	40.7	72
	29	10.00	53.3	73
	30	25.09	57.1	69
	31	0.51	55.9	37
	32	9.78	52.5	50
	33	58.97	56.5	61
	34	135.96	72.9	60
	35	6.91	50.2	78
	36	11.81	52.6	61
	37	3.47	55.9	74
	38	1.19	40.7	73
	39	0.00	40.7	72
	40	39.69	62.3	70

	PC-WUSPI	PROMIS	SCIM III
Group Avg. (std. dev.)	24.83 (±26.62)	55.85 (±8.82)	61.88 (±12.18)
A-A Avg. (std. dev.)	24.45 (±19.57)	58.37 (±8.28)	62.65 (±10.47)
A-P Avg (std. dev.)	25.22 (±32.74)	53.34 (±8.84)	61.10 (±13.91)

APPENDIX B – MATLAB code

WC Fit Code (partial):

```
%horizontal axle position
ACM = (RACR + LACR) / 2; %midpoint b/w the ac joints during top dead center
AM = (RWHEELTDC + LWHEELTDC) / 2; %midpoint b/w axle markers during TDC
HAP = (ACM(1,2)-AM(1,2)) / 10;
%Vertical axle position
VAP = (ACM(1,3)-AM(1,3)) / 10;%Vertical distance b/w axle and acromion marker
%backrest height (cm)
TMBR = mean(TMBR,"omitnan");
BLSeat = mean(BLSeat,"omitnan");
if TMBR(1,3) > 1
%BH = (TMBR(1,3)-BRSeat(1,3)) / 10;
BMSeat = (BRSeat + BLSeat) / 2; %Back Middle Seat (midpoint b/wcad BRSeat and
BLSeat)
BH = (sqrt(sum((TMBR-BMSeat).^2))) / 10;
%BH = (sqrt(sum((TRBR-BRSeat).^2))) / 10;
%alternative backrest height calculation for higher middle backrest in cm
elseif TMBR(1,3) == 0
BH = (sqrt(sum((TRBR-BRSeat).^2))) / 10;
%distance between 2 points
%back rest height in cm
end
%seat dump angle (deg)
FRSF = mean(FRSF,"omitnan");
BRSF = mean(BRSF,"omitnan");
seatslope = (FRSF(1,3)-BRSF(1,3))./(FRSF(1,2)-BRSF(1,2)); %this is the slope
in the z/x direction
SDA = atand(seatslope); %seat slope or seat dump angle in degrees relative to
floor
```

Statistics Code (this was edited as needed to included other metrics/variables):

```
%% LOADING IN DATA %%
BaseDir = 'C:\Users\';  % Set as you need
[FileName, FilePath] = uigetfile('*.xlsx', ...
                  'Please choose an Excel file', BaseDir);
if isequal(FileName, 0)
   disp('User aborted file choosing.');
   return;  % Assuming this is a function
end
File = fullfile(FilePath, FileName);
RawData = readmatrix(File);

%% RUNNING THE CORRELATIONS %%
% Age and YSI vs WUSPI/PROMIS/SCIM
[Rho_Age_WUSPI, p_Age_WUSPI] =
corr(RawData(1:40,3),RawData(1:40,7),'Type','Spearman','Rows','complete');
%age w Should Pain (PC-WUSPI)
```

```
[Rho_Age_PROMIS, p_Age_PROMIS] =
corr(RawData(1:40,3),RawData(1:40,8),'Type','Spearman','Rows','complete');
%age w PROMIS
[Rho_Age_SCIM, p_Age_SCIM] =
corr(RawData(1:40,3),RawData(1:40,9),'Type','Spearman','Rows','complete');
%age w SCIM
[Rho_YSI_WUSPI, p_YSI_WUSPI] =
corr(RawData(1:40,4),RawData(1:40,7),'Type','Spearman','Rows','complete');
%YSI w Shoulder pain (pc-wuspi))
[Rho_YSI_PROMIS, p_YSI_PROMIS] =
corr(RawData(1:40,4),RawData(1:40,8),'Type','Spearman','Rows','complete');
%YSI w PROMIS
[Rho_YSI_SCIM, p_YSI_SCIM] =
corr(RawData(1:40,4),RawData(1:40,9),'Type','Spearman','Rows','complete');
%YSI w SCIM

% HAP/VAP/THWS-Ratio vs WUSPI/PROMIS/SCIM
[Rho_HAP_WUSPI, p_HAP_WUSPI] =
corr(RawData(1:40,10),RawData(1:40,7),'Type','Spearman','Rows','complete');
%HAP w Should Pain (PC-WUSPI)
[Rho_HAP_PROMIS, p_HAP_PROMIS] =
corr(RawData(1:40,10),RawData(1:40,8),'Type','Spearman','Rows','complete');
%HAP w PROMIS
[Rho_HAP_SCIM, p_HAP_SCIM] =
corr(RawData(1:40,10),RawData(1:40,9),'Type','Spearman','Rows','complete');
%HAP w SCIM

[Rho_VAP_WUSPI, p_VAP_WUSPI] =
corr(RawData(1:40,11),RawData(1:40,7),'Type','Spearman','Rows','complete');
%VAP w Should Pain (PC-WUSPI)
[Rho_VAP_PROMIS, p_VAP_PROMIS] =
corr(RawData(1:40,11),RawData(1:40,8),'Type','Spearman','Rows','complete');
%VAP w PROMIS
[Rho_VAP_SCIM, p_VAP_SCIM] =
corr(RawData(1:40,11),RawData(1:40,9),'Type','Spearman','Rows','complete');
%VAP w SCIM

[Rho_THWSRatio_WUSPI, p_THWSRatio_WUSPI] =
corr(RawData(1:40,12),RawData(1:40,7),'Type','Spearman','Rows','complete');
%THWS-Ratio w Shoulder pain (pc-wuspi))
[Rho_THWSRatio_PROMIS, p_THWSRatio_PROMIS] =
corr(RawData(1:40,12),RawData(1:40,8),'Type','Spearman','Rows','complete');
%THWS-Ratio w PROMIS
[Rho_THWSRatio_SCIM, p_THWSRatio_SCIM] =
corr(RawData(1:40,12),RawData(1:40,9),'Type','Spearman','Rows','complete');
%THWS-Ratio w SCIM

% BH/SDA/SWSW-Ratio vs WUSPI/PROMIS/SCIM
[Rho_BH_WUSPI, p_BH_WUSPI] =
corr(RawData(1:40,14),RawData(1:40,7),'Type','Spearman','Rows','complete');
%BH w Should Pain (PC-WUSPI)
[Rho_BH_PROMIS, p_BH_PROMIS] =
corr(RawData(1:40,14),RawData(1:40,8),'Type','Spearman','Rows','complete');
%BH w PROMIS
```

```
[Rho_BH_SCIM, p_BH_SCIM] =
corr(RawData(1:40,14),RawData(1:40,9),'Type','Spearman','Rows','complete');
%BH w SCIM

[Rho_SDA_WUSPI, p_SDA_WUSPI] =
corr(RawData(1:40,16),RawData(1:40,7),'Type','Spearman','Rows','complete');
%SDA w Should Pain (PC-WUSPI)
[Rho_SDA_PROMIS, p_SDA_PROMIS] =
corr(RawData(1:40,16),RawData(1:40,8),'Type','Spearman','Rows','complete');
%SDA w PROMIS
[Rho_SDA_SCIM, p_SDA_SCIM] =
corr(RawData(1:40,16),RawData(1:40,9),'Type','Spearman','Rows','complete');
%SDA w SCIM

[Rho_SWSWRatio_WUSPI, p_SWSWRatio_WUSPI] =
corr(RawData(1:40,15),RawData(1:40,7),'Type','Spearman','Rows','complete');
%SWSWRatio w Shoulder pain (pc-wuspi))
[Rho_SWSWRatio_PROMIS, p_SWSWRatio_PROMIS] =
corr(RawData(1:40,15),RawData(1:40,8),'Type','Spearman','Rows','complete');
%SWSWRatio w PROMIS
[Rho_SWSWRatio_SCIM, p_SWSWRatio_SCIM] =
corr(RawData(1:40,15),RawData(1:40,9),'Type','Spearman','Rows','complete');
%SWSWRatio w SCIM

%% RANK SUM TESTS%%
WUSPI_groupdiff = ranksum(RawData(1:20,7),RawData(21:40,7));
PROMIS_groupdiff = ranksum(RawData(1:20,8),RawData(21:40,8));
SCIM_groupdiff = ranksum(RawData(1:20,9),RawData(21:40,9));

HAP_groupdiff = ranksum(RawData(1:20,10),RawData(21:40,10));
VAP_groupdiff = ranksum(RawData(1:20,11),RawData(21:40,11));
BH_groupdiff = ranksum(RawData(1:20,14),RawData(21:40,14));
SDA_groupdiff = ranksum(RawData(1:20,16),RawData(21:40,16));

THWS_groupdiff = ranksum(RawData(1:20,12),RawData(21:40,12));
SWSW_groupdiff = ranksum(RawData(1:20,15),RawData(21:40,15));


%% OUTPUTING CORRELATION RESULTS%%
header = {'Age vs WUSPI','Age vs Promis','Age vs SCIM','YSI vs WUSPI','YSI vs
Promis','YSI vs SCIM',...
    'HAP vs WUSPI','HAP vs Promis','HAP vs SCIM','VAP vs WUSPI','VAP vs
Promis','VAP vs SCIM',...
    'BH vs WUSPI','BH vs PROMIS','BH vs SCIM','SDA vs WUSPI','SDA vs
PROMIS','SDA vs SCIM','THWS Ratio vs WUSPI','THWS Ratio vs Promis','THWS Ratio
vs SCIM'...
    'SWSW Ratio vs WUSPI','SWSW Ratio vs PROMIS','SWSW Ratio vs SCIM'};
output =
[p_Age_WUSPI,p_Age_PROMIS,p_Age_SCIM,p_YSI_WUSPI,p_YSI_PROMIS,p_YSI_SCIM,p_HAP
_WUSPI,p_HAP_PROMIS,p_HAP_SCIM,...

p_VAP_WUSPI,p_VAP_PROMIS,p_VAP_SCIM,p_BH_WUSPI,p_BH_PROMIS,p_BH_SCIM,p_SDA_WUS
PI,p_SDA_PROMIS,p_SDA_SCIM,p_THWSRatio_WUSPI,...

p_THWSRatio_PROMIS,p_THWSRatio_SCIM,p_SWSWRatio_WUSPI,p_SWSWRatio_PROMIS,p_SWS
```

```
WRatio_SCIM;Rho_Age_WUSPI,Rho_Age_PROMIS,Rho_Age_SCIM,Rho_YSI_WUSPI,Rho_YSI_PR
OMIS,...

Rho_YSI_SCIM,Rho_HAP_WUSPI,Rho_HAP_PROMIS,Rho_HAP_SCIM,Rho_VAP_WUSPI,Rho_VAP_P
ROMIS,Rho_VAP_SCIM,...

Rho_BH_WUSPI,Rho_BH_PROMIS,Rho_BH_SCIM,Rho_SDA_WUSPI,Rho_SDA_PROMIS,Rho_SDA_SC
IM,Rho_THWSRatio_WUSPI,...

Rho_THWSRatio_PROMIS,Rho_THWSRatio_SCIM,Rho_SWSWRatio_WUSPI,Rho_SWSWRatio_PROM
IS,Rho_SWSWRatio_SCIM];

slash = '/';
FileOutputPath = 'C:\Users\bpatt\Desktop\';
filename = strcat(FileOutputPath,slash,'BP_Thesis_Stats_correl.csv');
if isfile(filename)
    disp('file exists');
else
    writecell(header,filename);
end

%export
writematrix(output,filename,'WriteMode','append');

%% OUTPUTTING GROUP DIFF STATS %%

header = {'WUSPI group diff','PROMIS group diff','SCIM group diff','HAP
diff','VAP diff','BH diff','SDA diff'...
    'THWS diff','SWSW diff'};
output =
[WUSPI_groupdiff,PROMIS_groupdiff,SCIM_groupdiff,HAP_groupdiff,VAP_groupdiff,B
H_groupdiff,SDA_groupdiff,...
    THWS_groupdiff,SWSW_groupdiff];

slash = '/';
FileOutputPath = 'C:\Users\bpatt\Desktop\';
filename = strcat(FileOutputPath,slash,'BP_Thesis_Stats_groupdiff.csv');
if isfile(filename)
    disp('file exists');
else
    writecell(header,filename);
end

%export
writematrix(output,filename,'WriteMode','append');

%% LOADING IN DATA FOR SW DATA%%
BaseDir = 'C:\Users\bpatt\OneDrive\Desktop\OneDrive -
bpatteronuw\OneDrive\Documents\Thesis Materials';  % Set as you need
[FileName, FilePath] = uigetfile('*.xlsx', ...
                  'Please choose an Excel file', BaseDir);
if isequal(FileName, 0)
   disp('User aborted file choosing.');
   return;  % Assuming this is a function
end
```

```
File = fullfile(FilePath, FileName);
RawData = readmatrix(File);

%% RUNNING CORRELATIONS FOR SW vs WC FIT PARAMS. %%
[Rho_BH_Ftot, p_BH_Ftot] =
corr(RawData(1:34,9),RawData(1:34,2),'Type','Spearman','Rows','complete');
%backrest height and resultant force
[Rho_BH_cad, p_BH_cad] =
corr(RawData(1:34,9),RawData(1:34,4),'Type','Spearman','Rows','complete');
%backrest height and cadence

[Rho_HAP_Ftot, p_HAP_Ftot] =
corr(RawData(1:34,10),RawData(1:34,2),'Type','Spearman','Rows','complete');
%horizontal axle position and resultant force
[Rho_HAP_cad, p_HAP_cad] =
corr(RawData(1:34,10),RawData(1:34,4),'Type','Spearman','Rows','complete');
%horizontal axle position and cadence

%% OUTPUTTING STATS FOR SW vs WC FIT PARAMS. CORRELATIONS%%
header = {'BH vs Resultant','BH vs Cadence','HAP vs Resultant','HAP vs
Cadence'};
output =
[p_BH_Ftot,p_BH_cad,p_HAP_Ftot,p_HAP_cad;Rho_BH_Ftot,Rho_BH_cad,Rho_HAP_Ftot,R
ho_HAP_cad];

slash = '/';
FileOutputPath = 'C:\Users\bpatt\Desktop\';
filename = strcat(FileOutputPath,slash,'BP_Thesis_Stats_SWvsWCfit.csv');
if isfile(filename)
    disp('file exists');
else
    writecell(header,filename);
end

%export
writematrix(output,filename,'WriteMode','append');
```