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Effects of Seat and Axle Position on Pain, Pathology, and Independence in Pediatric Manual Wheelchair Users with Spinal Cord Injury

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EFFECTS OF SEAT AND AXLE POSITION ON PAIN, PATHOLOGY, AND INDEPENDENCE IN PEDIATRIC MANUAL WHEELCHAIR USERS WITH SPINAL CORD INJURY

by

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ABSTRACT

EFFECTS OF SEAT AND AXLE POSITION ON PAIN, PATHOLOGY, AND INDEPENDENCE IN PEDIATRIC MANUAL WHEELCHAIR USERS WITH SPINAL CORD INJURY

by

Hannah Frank

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Under the Supervision of Professor Brooke A. Slavens, PhD

Manual wheelchair (MWC) users with spinal cord injury (SCI) rely heavily on their upper extremities to complete daily occupations. Due to repetitive shoulder use during wheelchair mobility and propulsion, MWC users are at greater risk of shoulder pain and shoulder pathology, and thus decreased independence, and lower quality of life. The relative fit of the wheelchair and its parameters are critical and can further impact the user's propulsion biomechanics. Parameters such as seat angle and axle position may put the user in detrimental shoulder positions for longer periods of time, impacting health outcomes even more. Although the effects of wheelchair setup on health outcomes have been explored in adult populations, little is known about the impact on pediatric MWC users, which is unfortunate because these children will live with the secondary medical conditions of an SCI longer than their adult counterparts. Limited research also exists on the wheelchair parameters currently being used by pediatric MWC users with SCI, and there are very few recommendations for wheelchair setup and fit specific to the pediatric population. This study aims to explore the seat and axle positions that are currently being used by pediatric MWC users with SCI, to identify the presence of shoulder pain and pathology in this population, and to determine if the relative fit of the pediatric wheelchair is related to pain, pathology, or independence scores in children with SCI. A total of 9 pediatric MWUs with SCI, ages 6-21, participated in this study. Three-dimension (3D) kinematics data were collected using 14-camera Vicon (Oxford Metric Group, Oxford, UK) Vantage and TS motion analysis systems. Shoulder pathologies were identified using diagnostic and quantitative ultrasound. Pain and independence outcomes were analyzed using the Wheelchair Users Shoulder Pain Index (WUSPI) and the Spinal Cord Independence Measure (SCIM). The mean seat angle used by the group was 5.16 degrees of elevation. Of the 9 participants, 7 used rearward axle positions in relation to their shoulders, while 2 used the adult recommended, forward axle position. Similarly, 4 of the participants followed the adult guideline to have an elbow flexion angle between 100-120 degrees, while 5 of the participants had their axles positioned non-optimally in the vertical direction according to adult guidelines. Shoulder pathologies were identified in 44% of the participants, and the average occupation ratio (percentage of the subacromial space occupied by the supraspinatus tendon) for the supraspinatus tendon was 69.62%. The average WUSPI score for the group was a 3.40 out of 150, and 4 of the 9 participants reported experiencing some level of shoulder pain on the assessment. The average SCIM score for all participants was a 67.13 out of 100, with age and time since injury strongly and significantly correlating with independence scores. After analyzing the data, a strong negative correlation between seat angle and occupation ratio was found. There was also a moderate correlation between the use of a non-optimal elbow angle and a higher WUSPI score. Finally, there was a strong positive correlation between seat angle and SCIM independence scores. Only weak correlations were found between horizontal axle positioning and the various outcomes, unlike in the adult population. Results of this study will

help to inform clinical decision-making when prescribing wheelchairs to children with SCI and when making wheelchair setup recommendations to pediatric MWC users and their families.

I would like to dedicate this project to my husband, Peter. Your love and support have gotten me through every challenge and have made every success more worthwhile. To my parents, Bob and Julie. Thank you for instilling in me the sense of hard work and determination that has gotten me to where I am today. And finally, to my mentors, Dr. Brooke Slavens and Dr. Matthew Hanks. Your dedication and knowledge have been invaluable throughout this entire process.

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I. Introduction

Roughly 1,500 children are admitted to hospitals in the United States each year for the treatment of spinal cord injury (SCI) (ASIA, 2020). Following their injury, a large percentage of these children will require the use of a mobility device to aid in ambulatory tasks. In fact, it is estimated that more than 300,000 children in the United States, ages 5 to 17 years, were using a wheelchair for functional mobility in 2014 (Taylor, 2018). Although manual wheelchairs (MWCs) can provide children with better access to play, education, peer relationships, and independence, wheeled mobility can be a hinderance to this population as well. Inaccessible environments, social stigma, and inappropriate wheelchairs can greatly affect a child's occupational performance as they learn to navigate their surroundings with a disability. For example, the relative fit of a wheelchair can greatly affect a user's social participation, health, and quality of life (Chaves et al., 2004; Di Marco et al., 2003; Winkler et al., 2008). Several studies have found that wheelchair parameters, such as the axle position, seat angle, backrest height, or wheel diameter can influence the efficiency and long-term effects of wheelchair propulsion (Boninger et al., 2000; Cowan et al., 2009; Giner-Pascual et al., 2011; Van Der Linden et al., 1996; Yang et al., 2012). If a wheelchair is not properly fitted to a user's needs, preferences, and physical limitations, it can cause discomfort and inefficient wheelchair propulsion. Unfortunately, a large percentage (anywhere from 41-68%) of wheelchairs are not properly fitted to MWC users based on clinical guidelines or user preferences (Alm et al., 2003; Mann et al., 1996; Medola et al., 2014). Wheelchair fit can be particularly challenging for pediatric MWC users due to the fact that children grow at such a rapid rate, insurance companies will only pay for a wheelchair every 3 to 5 years, and no clinical recommendations currently exist for this population (Krey, 2005; Krey & Calhoun, 2004).

Statement of the Problem

Due to limited insurance funding, the lack of fully adjustable wheelchairs, and the likelihood that a pediatric MWC user will quickly outgrow a customized setup, pediatric wheelchairs are often not properly fitted to the child for optimal performance (Krey, 2005; Krey & Calhoun, 2004). Although several research studies have looked at the effects of wheelchair setup and fit on the presence of shoulder pain, shoulder pathology, and wheelchair propulsion efficiency in adult manual wheelchair users with SCI, little is known about the wheelchair settings currently being used by pediatric MWC users and their effects on the presence of shoulder pain or pathology in children with SCI (Boninger et al., 2000; Boninger et al., 2001; Cowan et al., 2009; Giner-Pascual et al., 2011; Van Der Linden et al., 1996; Yang et al., 2012). When compared to those whose seats are positioned at an acute angle, adult MWC users with straight seat angles have shown to have higher prevalence of shoulder injury and shoulder pain (Giner-Pascual et al., 2011). Similarly, a more rearward horizontal axle position and a suboptimal vertical axle position (based on the elbow angle at top-dead center of the pushrim) have also shown to correlate with dangerous shoulder biomechanics and an increased risk of shoulder injury (Boninger et al., 2000; Kotajarvi et al., 2004; Van der Woude et al., 2009). Based on this research, clinical guidelines and recommendations have been created for adult MWC users to reduce their risks of repetitive use injury and impingement (Paralyzed Veterans of America Consortium for Spinal Cord, 2005). No such guidelines or recommendations exist that specifically address the proper wheelchair setup and propulsion techniques for pediatric MWC users (Krey & Calhoun, 2004).

Purpose

The purpose of this thesis was to explore the seat and axle positions that are currently being used by pediatric MWC users with SCI, to identify the presence of shoulder pain and pathology in pediatric MWC users with SCI, and to determine if the relative fit of the pediatric wheelchair is related to pain, pathology, or independence scores in children with SCI. Hopefully these findings will help to inform clinicians when prescribing wheelchairs to children with SCI or when making wheelchair setup recommendations to pediatric MWC users and their families.

Aims and Hypotheses

Aim #1: To determine the seat angles, horizontal axle positions, and vertical axle positions being used by pediatric manual wheelchair (MWC) users.

Hypothesis #1a: It is expected that pediatric MWC users will use straight seat positions as opposed to more acutely elevated seat angles.

Hypothesis #1b: It is expected that pediatric MWC users will have axles that are horizontally positioned more rearward in relation to the shoulder during wheelchair propulsion rather than more neutral or forward positioned.

Hypothesis #1c: It is expected that most pediatric MWC users will have axles that are positioned non-optimally in the vertical axis. This will be measured as elbow flexion angles that fall outside of the recommended 100-120 degrees when the hand is at top-dead center of the pushrim.

<u>Aim #2:</u> To determine if level of injury, age, or time since spinal cord injury (SCI) influence seat angle and axle position in the pediatric MWC user population.

Hypothesis #2a: It is expected that pediatric patients with SCI will have different seat angles based on their level of injury, age, and the time since their injury.

Hypothesis #2b: It is expected that pediatric patients with SCI will have different horizontal axle positions based on their level of injury, age, and the time since their injury.

Hypothesis #2c: It is expected that pediatric patients with SCI will have different vertical axle positions based on their level of injury, age, and the time since their injury.

<u>Aim #3:</u> To correlate supraspinatus tendon thickness in pediatric MWC users to wheelchair seat angles and axle positions.

Hypothesis #3a: It is expected that pediatric MWC users with SCI who use straighter wheelchair seat angles will have larger supraspinatus tendon thickness measurements as compared to those with more angled seats.

Hypothesis #3b: It is expected that pediatric MWC users with SCI whose wheelchair axles are positioned more rearward in relation to the shoulder during wheelchair propulsion will have larger supraspinatus tendon thickness measurements as compared to those with more neutral or forward axle positioning.

Hypothesis #3c: It is expected that pediatric MWC users with SCI whose elbow angles are positioned outside the standard range of flexion (i.e. non-optimal vertical axle position) will have larger supraspinatus tendon thickness measurements as compared to those with optimal elbow and vertical axle positioning.

<u>Aim #4:</u> To correlate shoulder pain in pediatric MWC users, as measured by the Wheelchair Users Shoulder Pain Index (WUSPI), to wheelchair seat angle and axle position.

Hypothesis #4a: It is expected that pediatric MWC users with SCI who use straighter seat angles will have higher shoulder pain intensities measured by the WUSPI than those with more acute seat angles.

Hypothesis #4b: It is expected that pediatric MWC users with SCI whose axles are positioned more rearward in the horizontal axis will have higher shoulder pain intensities measured by the WUSPI than those with more neutral of forward axle positioning.

Hypothesis #4c: It is expected that pediatric MWC users with SCI whose axles are positioned non-optimally in the vertical axis will have higher shoulder pain intensities measured by the WUSPI than those whose axles are positioned optimally.

<u>Aim #5:</u> To correlate pediatric MWC users' independence levels, as measured by the Spinal Cord Independence Measure (SCIM), to wheelchair seat angle and axle position.

Hypothesis #5a: It is expected that pediatric MWC users with SCI who use straighter seat angles will have lower independence levels measured by the SCIM than those with more acute seat angles.

Hypothesis #5b: It is expected that pediatric MWC users with SCI whose axles are positioned more rearward in the horizontal axis will have lower independence levels measured by the SCIM than those with more neutral or forward axle positioning.

Hypothesis #5c: It is expected that pediatric MWC users with SCI whose axles are positioned non-optimally in the vertical axis will have lower independence levels measured by the SCIM than those whose axles are positioned optimally.

Relevance to Occupational Therapy

Occupational therapists are responsible for ensuring that their clients can independently participate in meaningful occupations. For pediatric MWUs with SCI, meaningful occupations may include playing sports, socializing with peers, or attending school. There are many factors that may affect how successfully a child engages in these occupations, but for children with SCI, their wheelchair is an enormous factor. Manual wheelchairs can provide independence, freedom, and participation opportunities to children with SCI, but they may also exacerbate other health risks (Casey et al., 2017). If properly configured, a manual wheelchair can support an individual in successfully engaging with his or her environment, but if the device does not meet the needs of the user, it may further isolate the individual, increase pain, or hinder functional independence (Chaves et al., 2004; McClure et al., 2009). Proper wheelchair parameters and seating positions that fit an individual's physical and environmental needs can help to improve comfort, decrease pain, and increase independence for MWC users (Casey et al., 2017). Unfortunately, few guidelines or recommendations exist on proper fitting and use of pediatric manual wheelchairs. Often children and their families must wait long periods of time and spend large amounts of money only to receive a poorly fitted wheelchair with no education on how to properly adjust the device to fit their growing bodies (Bray et al., 2014). This is especially true for those who live in low-income areas as residents of these regions often have limited access to funding, rehabilitation services, education, and choice in wheelchair provision (WHO, 2008). To improve health outcomes and potentially decrease levels of shoulder pain and pathology in this population, standardized wheelchair prescription and fitting recommendations are still needed for younger age groups. Occupational therapists are well-equipped to create, facilitate, and implement these clinical guidelines for safer wheelchair use in the pediatric population, and they can provide pediatric MWC users with the activity modifications and wheelchair adjustments they need to achieve independence, successfully complete their meaningful occupations, and more easily interact with their environments (Stankovits, 2000). Occupational therapists collaborate with pediatric MWC users to create client-centered goals and to address the personal, environmental, and occupational factors that are inhibiting their occupational performance and participation. By understanding how children with SCI interact with their wheelchairs and how this interaction may affect shoulder pain and/or pathology, clinicians can provide better education to their clients and better support childhood engagement in meaningful occupations.

According to the Person-Environment-Occupation-Performance (PEOP) model, the personal, environmental, and occupational factors acting on an individual can equally affect their participation and performance in meaningful occupations (O'Brien & Kuhaneck, 2019) (Figure 1). This client-centered model encourages collaboration with the individual and emphasizes using their narrative to better facilitate changes to the internal and external factors that affect their overall participation and well-being (O'Brien & Kuhaneck, 2019). In order to achieve occupational engagement, fulfill a higher purpose, and participate in meaningful activities, the individual must be able to interact with his or her environment appropriately and effectively. Unfortunately, children with SCI are often forced to overcome additional physical, mental, emotional, and environmental barriers to fulfill their potential and reach their occupational goals (O'Brien & Kuhaneck, 2019). One of the major factors that can either hinder or support their performance and participation is their wheelchair.

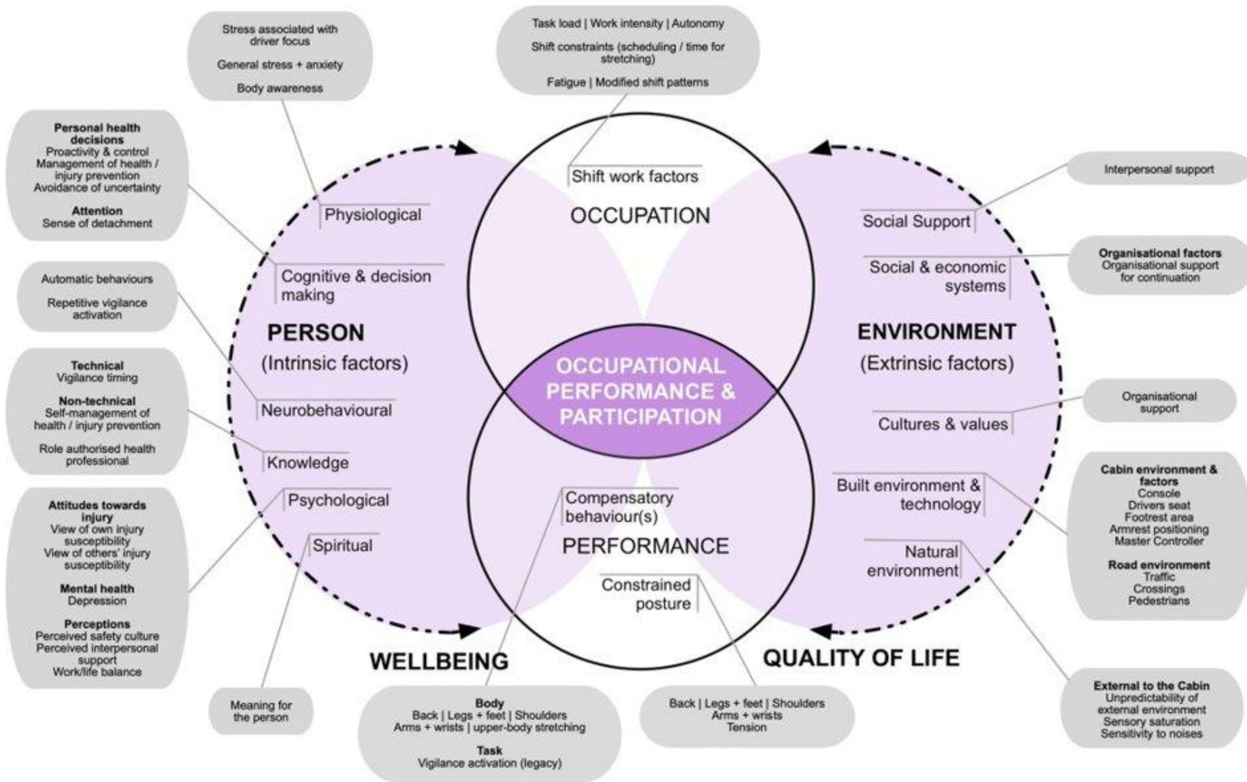


Figure 1: Person-Environment-Occupation-Performance (PEOP) model (Naweed et al., 2020).

In parallel with the PEOP model, the Person-Device-Environment model illustrates the impact that assistive devices have on people with disabilities and their ability to interact with the environment (Minkel, 2000; Stiens, 1998) (Figure 2). According to this model, changes to the immediate environment, the intermediate environment, and the community environment can influence how an individual interacts with their mobility device, and therefore, how they navigate their environment. The immediate environment relates to adjustments that can be made to reduce the person's impairment, such as adjusting the wheelchair settings to reduce risk of skin breakdown. The intermediate environment relates to environmental changes that can reduce the MWC user's functional limitations, such as providing dynamic seating options that restore functional mobility and increase independence. Lastly, the community environment involves the changes to the device that will increase participation, such as mental health therapy, wheelchair skills training, or programs to address social stigma (Minkel, 2000). Occupational therapists must be aware of each of these environmental contexts to best serve children with SCI who use manual wheelchairs.

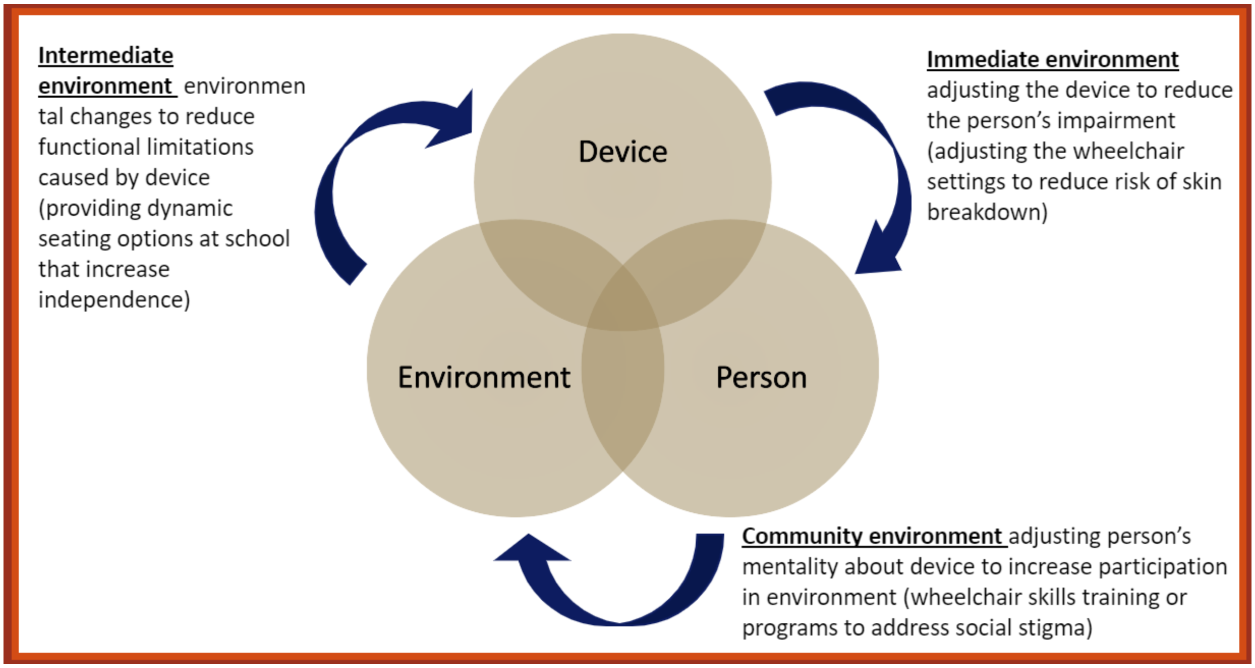


Figure 2: Person-Device-Environment model (Minkel, 2000)

Proper wheelchair seating and fitting is especially important in pediatric populations because as children with SCI age, their pain and upper extremity function are more greatly affected (Vogel et al., 2011; Zebracki et al., 2010). In addition, independent mobility and social participation are extremely important to childhood growth and development. Children with SCI are less likely to participate in formal activities outside of the home, but when encouraged to do so this leads to higher quality of life (Kelly et al., 2012; Klaas et al., 2010). Without access to independent mobility, a child may not be able to explore their environment through play, build social relationships with their peers, or engage in meaningful childhood occupations. Even if a child does have access to a mobility device, if that device is not configured to their specific needs and strengths, the child may still struggle to engage with their surroundings and to complete their occupations. According to the occupation-driven PEOP model, to achieve optimal performance, the wheelchair needs to facilitate the child's chosen occupations (O'Brien & Kuhaneck, 2019).

Similarly, if wheelchair propulsion is done improperly by pediatric MWC users, it may lead to pain and tissue damage in the shoulder later in life (Slavens, Schnorenberg, Aurit, Tarima, et al., 2015). Thankfully, pediatric MWC users can be trained to optimize their upper extremity function and to avoid dangerous joint positions through wheelchair skills training programs. Wheelchair skills training has been proven to increase pediatric independence and functional mobility following SCI, but these and other safety programs are not offered to every child who receives a wheelchair (McCann et al., 2017; Sawatzky et al., 2012). Children who do not receive proper training following wheelchair prescription may lack the skills and knowledge necessary to safely move around their environment. On the other hand, children who receive rehabilitation services, such as occupational therapy, following their SCI have shown improved functional skills and increased independence (Choksi et al., 2010). To best serve this population, however, more research needs to be conducted on proper pediatric manual wheelchair setup and use.

The toll of overcoming a life-changing injury, re-integrating into society, and adapting to daily activities in a wheelchair can impact a variety of health outcomes for children with SCI.

Pediatric patients with SCI face chronic pain, depression, anxiety, social isolation, and stigma following their injuries and these outcomes can be exacerbated by manual wheelchair use. That is why an increase in occupational therapy geared towards addressing the negative consequences of repetitive wheelchair use could potentially thwart some of these dangerous consequences. For example, children with SCI may benefit from receiving mental health interventions and positive coping strategies to improve their attitudes surrounding their disability, and ultimately, their occupational performance. Pain management therapy and other programs that address independence, social participation, intimacy, and emotional regulation could all help improve outcomes for these individuals as well. Finally, therapies focusing on advocacy and inclusion to decrease the stigma surrounding children with physical disabilities could enhance the quality of life for these individuals as well. For example, more accessible schools, parks, and community programs would help these children to integrate into society following their injuries. Overall, more research on pediatric manual wheelchair users with SCI could provide clinicians with valuable information on how to best serve this population.

Children with SCI who use manual wheelchairs are at risk of experiencing upper extremity pain, musculoskeletal pathology, and a series of other negative health outcomes throughout their lifetime (Osorio et al., 2014; Sawatzky et al., 2005; Vogel et al., 2002; Zebracki et al., 2010). Subsequent medical conditions, changes in activity demands, and inadequate assistive equipment can all lead to even more undesirable outcomes. More research in the areas of pediatric-onset SCI, proper wheelchair prescription, and the effects of wheelchair fit on pediatric health outcomes is needed to better aid clinicians in understanding what parameters might support or hinder pediatric manual wheelchair propulsion. This information can then better inform the therapist’s interventions and decision-making for the pediatric population (O'Brien & Kuhaneck, 2019).

II. Literature Review

Manual Wheelchair Users

Prevalence

According to the 2014 Americans with Disabilities report, 48.2 million adults in the United States have a functional limitation, 17.6% of which are lower body limitations (Taylor, 2018). More than 32.3 million individuals in the United States over the age of 15 (13.4% of the population) report having difficulty with lower body ambulatory functions, such as walking or climbing stairs (Taylor, 2018). A majority of these people require mobility aids, including wheelchairs and walkers, to navigate their environments and to complete their daily tasks safely and independently. In the United States alone, 18.4 million adults, roughly 8% of the population, use an assistive walking device, such as a cane, crutches, or walker, and 5.5 million Americans (2.3% of the population) rely on a wheelchair for ambulatory tasks (Taylor, 2018).

Although older adults (65 years or older) make up a majority of ambulatory device users, with roughly 2.0 million people in this age group using a wheelchair and 7.0 million using other forms of mobility aids, mobility devices are commonly used in younger populations as well (Brault, 2012). In fact, the manual wheelchair is the most common mobility device used by individuals under the age of 18 (Kaye et al., 2000). In 2014, 300,000 individuals under the age of 21 were using a wheelchair for functional mobility (Taylor, 2018).

Wheelchair Selection

For those who require a wheelchair due to weakness or paralysis, the process of selecting an appropriate device can be an overwhelming task. An individual may select a powered wheelchair or a manual wheelchair depending on his or her mobility needs and preferences. Typically, powered wheelchairs are larger, heavier, and more difficult to maneuver, but they require less physical function to operate. Manual wheelchairs, however, require more upper limb function, but tend to be less expensive, lighter, and easier to transport (Dudgeon et al., 2014). Although powered chairs are becoming more common, 90% of users still choose manual wheelchairs for functional mobility (Kaye et al., 2000).

Functional Mobility

In general, those with lower extremity disabilities face many challenges with activity restrictions and functional mobility limitations (Oyster et al., 2011). Even participating in activities of daily living (ADL), such as bathing and toileting, becomes complicated for those who can no longer stand or shift their weight efficiently. Access to a wheelchair, however, can facilitate the return of these individuals to their daily routines and meaningful activities (Chaves et al., 2004). For an individual who cannot navigate their home, school, or workplace without physical assistance, a wheelchair can provide pivotal independence and autonomy. Wheelchairs can even promote community integration and social participation for those with disabilities (Carlson & Myklebust, 2002). Access to independent functional mobility via a wheelchair enables participation in a variety of social, leisure, and community activities for people with disabilities (Di Marco et al., 2003). Overall, functional mobility is crucial for allowing individuals of all ages and abilities to access their environments and participate in their daily occupations.

Pediatric Mobility

Functional mobility is especially important for developing children as they begin to explore their changing environments and interact with their peers. The Centers for Disease Control and Prevention reports that regular physical activity and play are crucial for childhood health and even more important for those with mobility impairments, such as SCI (CDC, 2019). If a child with a mobility impairment lacks the physical ability to access his or her environment, a wheelchair can provide a safe and efficient method of ambulation (Cooper et al., 2008). By enabling mobility, wheelchairs can facilitate improved independence, social well-being, quality of life, participation, and physical activity in pediatric groups (Pousada García et al., 2015). One research study found that children with cerebral palsy were more likely to independently initiate mobility, communication, and social participation after learning how to use a powered wheelchair (Butler, 1986). Independent mobility in children has even been found to aid in cognitive and psychosocial development (Butler, 1986; Cooper et al., 2008). Another research study found that children who actively explored their environment performed better on spatial competency tests than those who did not (McComas et al., 1997). Children with mobility deficits who participated in active movement by independently propelling their wheelchair performed better on spatial memory tasks than those who were passively pushed by an adult (McComas et al., 1997). For children who have limited physical mobility, wheelchairs that allow the child to self-propel can greatly influence their ability to grow and interact with the world around them.

Shoulder Demands

Manual wheelchair (MWC) users rely heavily on their upper extremities for functional mobility and other daily activities. Not only are wheelchair users required to use their upper extremities for normal reaching and grasping tasks, but they are required to utilize their upper body for mobility tasks as well. In 2012, Sonenblum et al. proposed that the average wheelchair user spends 54 minutes propelling their wheelchair per day and traverses a total of 1.6 km. This study found that, on average, wheelchair users were propelling 10% of the time they were seated in their wheelchairs (Sonenblum et al., 2012). These repetitive upper body tasks can place significant stress on the joints and muscles of the shoulder. Pushing a wheelchair up an incline, transferring from a wheelchair into a car, and the repetitive motion of wheelchair propulsion may contribute to the mechanical stress exerted on the shoulders of manual wheelchair users (Brose et al., 2008).

Spinal Cord Injury

Incidence & Prevalence

It is estimated that approximately 250,000 to 500,000 people around the globe experience a spinal cord injury (SCI) each year (WHO, 2013) . According to the National Spinal Cord Injury Statistical Center, 17,900 of these occur in the United States each year, with roughly 252,000 to 373,000 people living with an SCI in the U.S. today (NSCISC, 2021) A large percentage of spinal cord injuries occur in older age groups, but many occur in younger populations as well. According to the American Spinal Cord Injury Association, 20% of all SCIs occur in children and adolescents, with 1455 children admitted to United States hospitals annually for SCI (ASIA, 2020). Overall, the incidence rate of SCI for the entire pediatric population (0-18 years old) in the United States was 26.9 per million from 1998 to 2012 (Saunders et al., 2015).

Etiology

Spinal cord injuries are often caused by traumatic events, such as motor vehicle accidents, sports-related injuries, gun shots, and falls (Jain et, 2015; Saunders et al, 2015). The National Spinal Cord Injury Statistical Center found that 38.2% of SCI's from 2015 to 2020 were caused by motor vehicle accidents, 32.3% from falls, 14.3% by acts of violence, 7.8% from sports injuries, and 7.4% were nontraumatic SCIs (NSCISC, 2021). Nontraumatic injuries may occur as a result of tumors, infections, genetic disorders, spinal stenosis, or ischemia (Atkins, 2014). A majority of SCIs occur in males ages 16 to 22 or in individuals over the age of 85 (Jain et al., 2015). Approximately 80% of all people with SCI are male, but the gap between male and female cases decreases with older and younger populations (Saunders et al., 2015; Vogel & DeVivo, 1996). The number of SCI's caused by falls is larger in the elderly population, while the majority of sports and violence related injuries occur in younger populations (Saunders et al., 2015). The number of firearms related cases also increases (14-18%) in younger adults ages 16 to 24, with a majority of those affected being male (Jain et al., 2015).

Pediatric populations experience unique etiologies of SCI due to physical and developmental changes prior to puberty. Lap-belt injuries, child abuse, birth defects, transverse myelitis, skeletal dysplasia, juvenile rheumatoid arthritis, and Down Syndrome are all examples of pediatric conditions that could predispose a child to SCI (Vogel et al., 2004). Bike-related accidents resulting in SCI are also higher for children ages 9 to 15 (Vogel & DeVivo, 1996).

Diagnosis & Classification

Spinal cord injuries are diagnosed and classified based on the location and severity of the injury. According to the American Spinal Injury Association (ASIA), an individual with an SCI can be classified as either tetraplegic or paraplegic. Tetraplegia is an impairment of the sensory and/or motor function in the cervical portion of the spinal cord, resulting in some degree of dysfunction in the arms, torso, legs, or pelvis (Atkins, 2014). Paraplegia is an impairment of the sensory and/or motor function in the thoracic, lumbar, or sacral portions of the spinal cord. Paraplegia does not affect the cervical spine, and therefore, still allows for arm function (Atkins, 2014). Spinal cord injuries can be further classified as either complete or incomplete. A complete SCI means that the individual lacks sensory and motor function in the lower sacral segment of the spinal cord, from the S4 to the S5 vertebra (Atkins, 2014). An incomplete injury is one in which the individual has some sensory and/or motor function below their level of injury. The neurological level of injury is determined as the lowest segment of the spinal cord at which the associated muscles score a grade 3 or higher on the manual muscle test and sensation in the associated dermatome is still intact (Atkins, 2014). To assess a patient's level of SCI severity, physicians use the ASIA Impairment Scale. According to this scale, an individual receives an A when the injury is complete, B when it is sensory incomplete, C for motor incomplete, D for incomplete, and E if their sensation and motor function are graded as normal (Atkins, 2014).

The severity of an SCI often varies depending on injury level. According to the National SCI Statistical Center, nearly half of all newly reported SCI's in the United States from 2015-2020 were cervical injuries resulting in complete tetraplegia (NSCISC, 2021). About 20% of all

SCI's resulted in incomplete paraplegia, 20% in complete paraplegia, 12% in complete tetraplegia, and less than 1% of those with SCI's experienced complete neurological recovery (NSCISC, 2021). Interestingly, the makeup of SCI injury levels also changes with age group. For example, younger populations are more likely to have paraplegia (67% of children) and/or complete (50% of children) injuries when compared to adults (Vogel et al., 2004). The most common injury site for children ages 0 to 8 is at the T1-T12 level while adolescents ages 8 to 21 are most commonly injured at the C4-C6 level (Vogel & DeVivo, 1996).

Prognosis & Secondary Conditions

The diagnosis of a spinal cord injury can be an overwhelming, life-changing event. Most people with SCI experience some level of paralysis, but neural recovery through rehabilitation is possible. In general, patients who have incomplete injuries have a better prognosis, but the life expectancy of the entire SCI population is only slightly less than average; the major causes of death being respiratory issues and infections (Atkins, 2014).

A variety of health problems and secondary conditions may occur as a result of an SCI. Autonomic dysreflexia, pressure ulcers, orthostatic hypotension, loss of bowel and bladder function, loss of sexual function, issues with temperature regulation, fatigue, spasticity, and deep vein thrombosis are common complications experienced by the SCI population (Atkins, 2014). In addition, an estimated 10-53% of individuals with SCI develop heterotopic ossification, a condition in which connective tissue calcifies around the joints due to disuse (Van Kuijk et al., 2002). These secondary conditions can make functional mobility and activities of daily living even more painful and strenuous for SCI patients. In fact, a large percentage of adults with SCI experience chronic pain as a result of their injury (Celik et al., 2012; Dijkers et al., 2009).

Increased levels of pain can affect mobility, social participation, and independence, which have been found to influence levels of depression, life satisfaction, substance abuse, and suicide rates among adults with SCI (Post & Van Leeuwen, 2012).

Pediatric Concerns

Compared to adults, children and adolescents with SCI may experience unique secondary conditions as they develop and reach puberty (Vogel et al., 2004). For example, infants and toddlers with SCI may be at higher risk of skin breakdown because they are more likely to scoot or crawl for mobilization (Vogel et al., 2004). Adolescents may be less likely to care for or report pressure ulcers to their parents in fear of social rejection or embarrassment. If left untreated, these wounds may lead to sepsis, osteomyelitis, or malnutrition and may require immobilization or surgical repair (Vogel et al., 2004).

Pressure ulcers may also be more common in children with SCI because of the high rates of hip deformities, specifically hip subluxations, that are seen in this population (Rink & Miller, 1990; Zebracki et al., 2010). Most children under the age of 10 and nearly all children under the age of 5 have been found to have hip instability, possibly due to the fact that children with SCI often experience some level of spasticity as well (Vogel et al., 2004). Other orthopedic complications, such as scoliosis, are also extremely common in children with SCI (Parent et al., 2011). Almost all children who experience an SCI before puberty develop scoliosis, and a majority of those cases require surgery. (Dearolf et al., 1990; Vogel et al., 2004). Young males with SCI are also more likely to develop hypercalcemia (Maynard, 1986). Hypercalcemia, or increased bone resorption due to immobilization, is more common in adolescent males because of their larger bone mass and higher levels of bone turnover during puberty (Vogel et al., 2004).

One other unique aspect of pediatric SCI is that children are more likely to experience spinal cord injury without radiographic abnormality (Pang & Wilberger, 1982; Parent et al., 2011). Children with this condition experience a spinal cord lesion, but they do not show signs of a spinal fracture or dislocation at the time of injury. More than 60% of children who sustain their SCI before the age of 5 have SCI without radiographic abnormality while only about 25% of older children have the syndrome (Vogel et al., 2004).

Shoulder Anatomy & Physiology

Shoulder Complex

The shoulder complex is made up of the scapula, the humerus, the clavicle, the sternum, and the ribs. There are five structures within the shoulder complex: the glenohumeral (GH) joint, the acromioclavicular (AC) joint, the sternoclavicular (SC) joint, the scapulothoracic (ST) articulation, and the subacromial space. These articulations allow the shoulder to move in either flexion/extension, adduction/abduction, internal/external rotation, horizontal adduction/abduction, or circumduction. The shoulder also relies on several muscles to create these movements. The rotator cuff muscles (the supraspinatus, infraspinatus, teres minor, and subscapularis) are major contributors to shoulder movement as well as the deltoid, serratus anterior, pectoralis major, and latissimus dorsi.

Several different bones make up the articulations of the shoulder complex. The shoulder girdle is made up of the clavicle and the scapula. The clavicle acts to protect the neurovascular structures beneath it by distributing forces to other parts of the body. It has a sternal end, acromial end, and a shaft where the deltoid, subclavius, pectoralis major, trapezius, sternocleidomastoid, and sternohyoid muscles attach. The scapula is integral to upper extremity movement at the shoulder because it acts as the attachment site for seventeen different muscles. The scapula articulates with the humeral head at the glenoid fossa, a concave portion of the scapula that tends to face about 30-40 degrees anterior to the frontal plane (Neumann, 2002). This orientation of the scapula at rest is known as the scapular plane. The largest bone in the body, the humerus, is the attachment site for several muscles as well, including the deltoid. The relationship between the head of the humerus and the humeral shaft is important in determining both the angle of inclination and the angle of retroversion, two parameters that may affect how an individual moves the shoulder (Schuenke et al., 2014). The sternum also provides an important articulating surface for the shoulder complex.

Shoulder Girdle

The shoulder girdle is made up of the SC joint, the AC joint, and the ST joint. The SC joint is the articulation between the sternal end of the clavicle and the manubrium, or superior end of the sternum. This saddle joint is the connection between the appendicular and axial skeletons. The SC joint allows for some elevation/depression, protraction/retraction, and rotation around the long axis of the clavicle, which places the scapula in an optimal position for articulating with the humerus (Neumann, 2002). Although the SC joint lacks boney stability, it has a tremendous amount of ligamentous support. The anterior sternoclavicular ligament, posterior sternoclavicular ligament, costoclavicular ligaments, and interclavicular ligament anchor the medial end of the clavicle to the sternum, stabilizing the SC joint (Epperson & Varacallo, 2019).

The AC joint is the articulation between the opposite end of the clavicle and the acromion process of the scapula. It is a flat joint, and therefore, requires strong ligaments to maintain stability. The acromioclavicular ligament prevents the clavicle from gliding over the acromion process while the coracoclavicular ligaments restrict movement of the clavicle in the superior and lateral directions. The coracoacromial ligament connects the acromion to the coracoid process of the scapula. The AC joint allows internal/external rotation, upward/downward rotation, and anterior/posterior tipping of the scapula (Schuenke et al., 2014).

The ST joint consists of loose connective tissue between the subscapularis and the serratus anterior muscles. This articulation runs along the posterior ribs and allows for easy movement of the scapula over the thoracic rib cage. Kinematics of the ST joint are a direct result of the combined movements of the SC and the AC joints. Together, these joints allow for scapular elevation/depression, protraction/retraction, and upward/downward rotation (Neumann, 2002). Below the acromion process is the subacromial space. This is a bursae-lined cavity that facilitates movement between the acromion and the rotator cuff muscles. The coracoacromial ligament forms the subacromial arch at this articulation, which stabilizes the humerus in the superior direction (Schuenke et al., 2014). Together, the serratus anterior, trapezius, rhomboids, levator scapulae, pectoralis minor, and subclavius muscles move the shoulder girdle.

Glenohumeral Joint

The head of the humerus articulates with the glenoid fossa of the scapula to form the GH joint. The GH joint has three degrees of freedom and allows for flexion/extension, abduction/adduction, internal/external rotation, horizontal abduction/adduction, and circumduction. The deltoid, supraspinatus, infraspinatus, teres minor, subscapularis, latissimus dorsi, teres major, pectoralis major, coracobrachialis, and biceps brachii facilitate these movements.

The angle of retroversion, or the 30 degree posterior angle at which the adult humeral head is usually rotated, allows the head of the humerus to align within the scapular plane and more effectively articulate with the scapula (Neumann, 2002). Children, however, have a larger angle of retroversion (about 65 degrees at birth) that decreases as they age, until it reaches the adult position (about 30 degrees) in between ages 16 and 20 (Krahl, 1946; Neumann, 2002). Several studies have shown that increased mechanical stresses on the shoulder during childhood may lead to greater angles of retroversion in adulthood (Neumann, 2002; Sabick et al., 2005; Wyland et al., 2012; Yamamoto et al., 2006).

Due to its shallow articulation and weaker ligaments, the GH joint is highly mobile but lacking in stability. Because the glenoid cavity is significantly smaller than the head of the humerus, extra support is needed to prevent dislocation. The subscapularis, supraspinatus, infraspinatus, and teres minor surround the GH joint capsule, structurally reinforcing it and providing protection during dynamic activity (Neumann, 2002). The long head of the biceps brachii prevents anterior translation of the humeral head as well. The cartilaginous glenoid labrum deepens the articulation between the head of the humerus and the glenoid fossa, while the surrounding tendons and ligaments of the joint capsule stabilize the joint. The three glenohumeral ligaments stabilize the joint anteriorly. The coracohumeral ligament runs from the coracoid process of the scapula to the greater tubercle of the humerus, and the transverse humeral ligament passes over the intertubercular groove of the humerus to support the biceps tendon (Schuenke et al., 2014). There are several bursae, or fluid-filled sacs, surrounding the GH joint capsule as well. These bursae eliminate friction and allow for smooth movement between the humerus and its surrounding tendons.

Scapulohumeral Rhythm

In order to fully abduct the arm at the shoulder, both the scapula and the humerus need to move simultaneously; this is accomplished in a movement pattern called scapulohumeral rhythm. The first 30 degrees of abduction occur at the GH joint as the humeral head rotates in the glenoid fossa, but past 30 degrees, the scapula must also start to rotate to achieve full range of motion. For every 2 degrees the GH joint abducts the arm, the ST joint rotates upward 1 degree, creating a 2:1 scapulohumeral rhythm ratio. When the arm is fully abducted to 180 degrees, 120-130 degrees occur by rotation of the humerus and 50-60 degrees occur by rotation of the scapula (Schuenke et al., 2014). Both movements are necessary to create room for the humerus as it moves upward into full shoulder abduction.

Nerves & Vasculature

The muscles and joints of the shoulder are innervated by a grouping of nerves called the brachial plexus. The brachial plexus stems from the C5 to T1 nerve roots and consists of the dorsal scapular, long thoracic, suprascapular, subclavian, medial pectoral, upper subscapular, thoracodorsal, brachial cutaneous, lower subscapular, and antebrachial cutaneous nerves as well as the axillary, radial, musculocutaneous, median, and ulnar terminal branches. This bundle of nerves runs posterior to the clavicle and inferior to the coracoid process of the scapula. Its compact location makes the supraclavicular brachial plexus very susceptible to paralysis or impingement during shoulder movement (Schuenke et al., 2014).

Each of the nerves of the brachial plexus innervates a group of muscles that contributes to upper extremity function. The musculocutaneous nerve innervates the biceps brachii, the brachialis, and the coracobrachialis. Injury to this nerve may affect an individual's ability to flex the shoulder. The median nerve innervates and provides sensory information to the palm and anterior forearm. The radial nerve innervates the triceps brachii and the brachioradialis. Shoulder dislocations or humeral fractures can lead to injury of the radial nerve. Lastly, the axillary nerve innervates the deltoid and the teres minor. This nerve allows an individual to abduct the arm at the shoulder and may be injured after trauma to the shoulder or humerus.

The clavicle and scapula not only shield these integral nerves, but they also protect the vascular structures that supply blood and nutrients to the shoulder. The subclavian artery becomes the axillary artery directly posterior and inferior to the clavicle. The axillary artery then has smaller branchings (the thoracoacromial, lateral thoracic, subscapular, posterior humeral circumflex, and anterior humeral circumflex) that supply blood to the shoulder structures before becoming the brachial artery farther down the forearm (Schuenke et al., 2014).

Shoulder Pathology

Glenohumeral Instability & Subacromial Impingement

Manual wheelchair users with SCI rely heavily on their upper extremities for mobility. Repetitive use and increased forces during wheelchair propulsion can lead to pain and injuries in the shoulder complex (Bayley et al., 1987; Finley & Rodgers, 2004). Two common causes of pain and dysfunction within the shoulder are glenohumeral instability and subacromial impingement (Finley & Rodgers, 2004). Related pathologies that may contribute to these core conditions include tendonitis, tendinosis, ligament tears, abnormal musculature, compression or abrasion of the rotator cuff tendons, bone spurs, and other soft tissue damage. Diagnosis of these shoulder pathologies can be done through special tests or clinical exams as well as with diagnostic imaging, such as magnetic resonance imaging (MRI), X-ray, and ultrasound.

Due to the shoulder's complex nature, shoulder instability can occur for a variety of reasons. The static stabilizers of the shoulder are the bones, ligaments, and glenoid labrum. The dynamic stabilizers are the muscles and tendons of the rotator cuff and scapulothoracic unit (Allen, 2008). Pathologies or injuries in any one of these areas can affect the structure and stability of the entire shoulder.

Subacromial impingement is a relatively common pathology that occurs when the tissues beneath the subacromial space are repeatedly compressed during shoulder abduction (Neumann, 2002; Van der Windt et al., 1995). In a healthy shoulder, the subacromial space is already narrow, usually between 3-10 mm (Giphart et al., 2012). Inflammation or migration of the humeral head during abduction can reduce the size of the subacromial space even more, leading to impingement (Neumann, 2002). Abnormal GH joint kinematics and scapular dyskinesis during shoulder abduction may also lead to increased subacromial impingement (Kibler et al., 2012; Lawrence et al., 2014; Neumann, 2002; Seitz et al., 2012). During subacromial impingement, the supraspinatus tendon, the long head biceps tendon, and the subacromial bursa can become compressed, resulting in shoulder pain, functional limitations, and potential rotator cuff syndrome (Ludewig & Cook, 2002; Neumann, 2002).

Rotator Cuff Abnormalities

The rotator cuff muscles as a unit provide most of the stability and mobility within the shoulder, but impingement or ischemia of these tissues can lead to weakness and decreased function. As mentioned above, the subacromial space is naturally narrow and becomes even more narrow during abduction. As this space tightens, underlying structures, such as the rotator cuff tendons can become impinged. Thickened subacromial bursa, calcifications on the coracoacromial ligament, glenohumeral subluxation, or rotator cuff tears can all result from shoulder impingement (Fongemie et al., 1998). Isolated tears of the infraspinatus, subscapularis, and teres minor are much less common, but they may result from the extension of a more common supraspinatus tendon tear (Allen, 2008).

The supraspinatus tendon is particularly susceptible to inflammation and tearing. Due to the muscle's short internal moment arm in shoulder abduction, the supraspinatus has a mechanical advantage of 1:20, and therefore, must produce extremely high forces to complete even the most basic daily activities (Neumann, 2002). These large forces may lead to tears, abrasion, or inflammation over time. The supraspinatus tendon is also considered significantly avascular, a characteristic that increases with age. This avascularity combined with natural degeneration can lead to partial, full thickness, or complete tears of the supraspinatus tendon (Allen, 2008). A partial tear of the supraspinatus is categorized as a tear of the bursa surrounding the tendon, a full thickness tear is a tear from the upper to lower surface of the tendon, and a complete tear is when the supraspinatus completely separates, revealing the underlying bone (Allen, 2008).

If a supraspinatus tear does extend to the posterior (infraspinatus and teres minor) and anterior (subscapularis) muscles of the rotator cuff, the shoulder becomes even more unstable. Ligament and tendon tears are common in the rotator cuff due to compression and abrasion, and this may lead to inflammation of the bursa or bursal wall thickening (Allen, 2008). There are three distinct types of tendon tears that are often seen in rotator cuff patients. In patients with rotator cuff tears, the most common variety occurs when the greater tuberosity roughens, and as a result, the supraspinatus tendon tears near its insertion point. Another common type occurs when the coracoacromial ligament becomes impinged in the subacromial space. If the coracoacromial ligament experiences more friction in the subacromial space it may produce osteophytes (bony growths) on the acromion (Mahakkanukrauh & Surin, 2003). These abnormal bone spurs in the AC joint may aggravate or even rupture the rotator cuff tendons. The last and least common type of rotator cuff tear occurs when there is posterior impingement of the supraspinatus and infraspinatus, resulting in posterior bursal damage (Allen, 2008).

Supraspinatus Tendon Thickness

A majority of pediatric shoulder lesions involve the supraspinatus tendon (78%), making it one of the most common areas for shoulder pathology to occur in the pediatric population (Perez et al., 2018). Although the supraspinatus tendon can provide clinicians with valuable information about an individual's shoulder health, mixed research exists surrounding the relationship between supraspinatus tendon thickness, pathology, and pain. In theory, an increase in supraspinatus tendon thickness can signify inflammation while a decrease in tendon thickness may indicate degeneration, but results vary on the correlations between supraspinatus tendon measurements, the presence of pain, and/or the existence of different shoulder pathologies across various groups.

Changes in supraspinatus tendon thickness or cross-sectional area can signify potential risk factors for different populations. For example, tendon thinning may be a sign of degeneration, indicating the need for surgical repair (Morag et al., 2006). Tendon degeneration can be assessed by finding the thickness of the tendon, the cross-sectional area of the tendon, or by calculating the occupation ratio (Morag, 2006). The occupation ratio is defined as the percentage of the subacromial space that is occupied by the supraspinatus tendon (Navarro-Ledesma et al., 2021). The occupation ratio can be calculated by dividing the supraspinatus tendon thickness by the acromiohumeral distance and multiplying by 100 (Navarro-Ledesma et al., 2021). If found to be less than 50%, this may indicate supraspinatus atrophy (Morag et al., 2006). In contrast, the occupation ratio can also provide information about tendon inflammation or tendon thickening. If the tendon is overworked, it could become inflamed, resulting in a larger occupation ratio and crowding in the subacromial space. For example, one study found that adult MWUs with SCI (N=16) have thicker supraspinatus tendons and larger occupation ratios than able-bodied individuals (N=16), indicating that the shoulder muscles of adult MWUs may be overused (Belley et al., 2017). This study did not, however, find a significant difference in tendon thicknesses between MWUs with and without shoulder pain (Belley et al., 2017). Overall, the occupation ratio has proven to be a valid measure for discriminating between MWUs with SCI and able-bodied individuals, indicating that this measure is an adequate way to record shoulder changes in this population (Belley et al., 2017).

Several studies have gone a step further to look at the effects of physical activity on shoulder pain and supraspinatus tendon thicknesses. One study looked at the effects of shoulder pain on tendon thickness changes following physical activity, and they found that when compared to pain-free shoulders those who had previously reported shoulder pain also experienced greater increases in supraspinatus tendon thicknesses following physical activity (Porter et al., 2020). Another study looked specifically at the effects of fatiguing wheelchair propulsion on the supraspinatus tendon thicknesses of manual wheelchair users with SCI (N=50) (Bossuyt et al., 2020). This study found that the supraspinatus tendon decreased an average of 1.39 mm following fatiguing wheelchair propulsion, which may relate to the high prevalence of shoulder injury in this population (Bossuyt et al., 2020). A third study looked at supraspinatus tendon thickness changes in those with painful rotator cuff injuries following exercise therapy (McCreesh et al., 2017). It was determined that who commonly reported shoulder pain (N=23) had a more significant increase in supraspinatus tendon thickness following physical activity than those with pain-free tendinopathy (N=20) (McCreesh et al., 2017). The results of this study suggest that individuals with painful supraspinatus tendinopathies may experience increased tendon thickening, a reduced subacromial space, and a higher risk of tendon compression following physical activity (McCreesh et al., 2017).

Although existing research groups have concluded that changes in supraspinatus tendon thickness can signify future risks of shoulder pathology and that supraspinatus dimension vary between able-bodied individuals and MWUs, several studies have found that supraspinatus tendon thickness may not be a strong indicator for shoulder pain. One such study found no correlation between supraspinatus tendon thickness and the presence of pain in subjects recovering from rotator cuff surgical repair (Tham et al., 2013). Similarly, Navarro-Ledesma et al. determined that the relationship between supraspinatus tendon thickness and shoulder pain was insignificant; they found that the tendon thicknesses between those with (N=62) and without (N=40) non-traumatic chronic shoulder pain were comparable (Navarro-Ledesma et al., 2019). Finally, as mentioned above, Belley et al. found no significant difference in tendon thicknesses between adult MWUs with and without shoulder pain (Belley et al., 2017).

Secondary Conditions

After a rotator cuff injury, secondary conditions may develop that can increase pain and dysfunction for affected individuals. For example, scar tissue or calcifications may form after a supraspinatus tendon tear, restricting shoulder range of motion (ROM) (Allen, 2008). Following scar tissue formation, neovascularization occurs as a part of the healing process, but hypervascularity in these typically avascular tendons may not necessarily enhance functional recovery. Instead, neovascularization of rotator cuff tendons may lead to excess scarring, decreased functional mobility, and increased pain post-healing (Tempfer & Traweger, 2015).

Conditions of the subdeltoid and subacromial bursa are also strong indicators of rotator cuff pathologies as bursitis commonly follows a tendon tear. Fluid may build up in these spaces after an acute injury, while more chronic conditions may result in complete loss of bursal fluid due to tissue degeneration (Allen, 2008). Synovitis or joint effusion are commonly seen in the AC and GH joints as a result of subluxation or inflammation in the shoulder (Allen, 2008). Overall, calcifications, scarring, and inflammation as a result of bursal or tendon tears can lead to shoulder instability, impingement, and ultimately a loss of function in the shoulder (Fongemie et al., 1998).

Tendonitis (thickening of tendon due to inflammation) and tendinosis (the degeneration of a tendon due to chronic overuse) of the long head of the biceps tendon are also common overuse injuries of the shoulder. Fluid buildup, proximal tearing, and subluxation of this tendon are all signs of shoulder injury that could potentially compromise the stability of the shoulder (Allen, 2008).

Special Tests & Diagnosis

Clinicians and researchers use many tools to determine the prevalence of musculoskeletal pathologies in individuals with shoulder pain. Special tests may be completed during physical exams or radiographic imaging may be used to get a more comprehensive look at the shoulder. There are several widely accepted special tests that clinicians use to diagnose or rule out shoulder abnormalities. If a patient experiences pain or discomfort during these special tests this signifies the probable presence of a shoulder pathology.

The empty can, Neer, Hawkins, and painful arc tests are often used clinically to diagnose subacromial impingement (Michener et al., 2009). The empty can test requires that the clinician apply resistance to shoulder abduction while the patient's shoulder is flexed to 90 degrees, horizontally abducted to 45 degrees, and internally rotated with the thumb facing down. A positive sign for this test, weakness or pain, would indicate a tear of the supraspinatus tendon (Maher, 2014). The Neer test aids in the identification of rotator cuff or biceps tendon impingement in the subacromial space. The clinician passively elevates the arm in the scapular plane while it is internally rotated. If the patient expresses pain this indicates compression of the supraspinatus and/or the long head of the biceps tendon (Maher, 2014). Another test that helps to identify subacromial impingement and rotator cuff tendonitis is the Hawkins Test. Here the clinician forces the flexed shoulder and elbow into internal rotation and horizontal adduction. If the patient experiences pain this indicates impingement or inflammation of the supraspinatus and/or biceps tendon (Maher, 2014). The painful arc test has the patient abduct their shoulders in a full arc. If they experience pain between 60 and 120 degrees of abduction, this is a positive sign for supraspinatus impingement (Michener et al., 2009).

The apprehension test, sulcus sign, and hyperabduction test are commonly used by clinicians to identify shoulder instability (Lizzio et al., 2017). During the anterior apprehension test, the patient abducts the arm to 90 degrees while the clinician externally rotates the arm and applies anterior pressure to the humerus. If the patient experiences pain or discomfort, this signifies anterior instability in the GH joint (Hawkins & Bokor, 1998). Similarly, if the patient complains of pain or discomfort in this position while the clinician internally rotates the arm and applies posterior pressure, then the patient likely has posterior instability in the GH joint (Hawkins & Bokor, 1998). The hyperabduction test also detects inferior instability in the GH joint. During this test, the clinician stabilizes the shoulder girdle while passively abducting the patient's arm. If the patient is able to abduct the shoulder past 105 degrees, this suggests GH joint instability (Lizzio et al., 2017). Another common provocative test for identifying inferior laxity of the GH joint is the sulcus sign. A positive sulcus sign occurs when the humeral head displaces after an inferior force is applied to the elbow (Lizzio et al., 2017).

Two other tests, the AC joint compression test and the biceps Speed's test aid in the diagnosis of other pathologies acting on the shoulder. The AC joint compression test can be used to determine if a patient has AC joint separation. The clinician firmly presses on both sides of the AC joint, compressing it. If the patient experiences extreme pain or abnormal movement, this is a positive sign for joint separation (Wallmann, 2010). The biceps Speed's test is used to test for bicipital tendinitis, impingement of the biceps tendon, or rotator cuff bursitis. The shoulder is flexed to 90 degrees, the forearm is extended in supination, and resistance is applied to flexion while the clinician palpates the bicipital groove. A positive sign is pain in the bicipital groove with palpation (Maher, 2014).

Overall, special tests have shown to be good predictors of musculoskeletal pathologies. For example, individuals who experience pain and discomfort in the supraspinatus during clinical exams tend to have higher scores for supraspinatus impingement during ultrasound exams than those who do not have discomfort (Brose et al., 2008). Similarly, subjects who have tenderness at the greater tuberosity (positive Neer sign) during clinical exam, are more likely to have cortical surface irregularity in the greater tuberosity as well as supraspinatus tendinopathy identified during ultrasound (Brose et al., 2008). The empty can test and the painful arc test have also shown to have good diagnostic utility and reliability in screening for subacromial impingement syndrome (Michener et al., 2009). Finally, the sulcus sign (gap between acromion and humerus with distal pull) and the apprehension test have demonstrated to good reliability in diagnosing instability in patients with shoulder pain as well (Tzannes et al., 2004).

Radiographic imaging is often used to verify special test results and to more accurately diagnose a shoulder pathology. MRI, X-ray, and ultrasound are most commonly used to identify these musculoskeletal abnormalities and injuries. Although both MRI and ultrasound are frequently used to assess joints and tendons, there are significant benefits to each. Ultrasound does not involve radiation, is cheaper, and can be done in real-time to allow dynamic examination of moving joints. MRI, however, may be easier to administer and interpret results

(Brose et al., 2008). Despite their clinical differences, MRI and ultrasound have been shown to have relatively comparable accuracy in identifying shoulder pathologies, such as full-thickness and partial-thickness rotator cuff tears (Iannotti et al., 2005; Teefey et al., 2004).

Prevalence of Pathology in Manual Wheelchair Users

Manual wheelchair users rely heavily on their upper body for mobility and occupational tasks, and therefore, may be at higher risk of developing shoulder pathologies. In several research studies, most of the MWC users imaged were found to have shoulder degenerative disorders, such as AC joint narrowing, AC degenerative joint disease, acromial edema, distal clavicular edema, coracoacromial ligament edema, or biceps tendonitis (Boninger et al., 2001; Finley & Rodgers, 2004; Lal, 1998; Mercer et al., 2006). Not all subjects were found to have shoulder degeneration, but a large percentage of the shoulders tested were found to have at least one of the following abnormalities: bone tissue necrosis, osseous spurs, nerve impingement, distal clavicular osteolysis, rotator cuff impingement, or GH instability (Boninger et al., 2001; Finley & Rodgers, 2004; Lal, 1998; Mercer et al., 2006). When compared to those without SCI, it was discovered that individuals with SCI were also more likely to have irregular GH joint space, GH joint effusion, and osteophytes in the AC joint (Kivimäki & Ahoniemi, 2008). More recently, Morrow et al. (2014) used MRI to look at the shoulders of MWC users who were experiencing pain at the time of the study. Of the shoulders imaged, 70% had tendon tears, and 100% had tendinopathy (Morrow et al., 2014). Other factors as well, such as gender, age, activity level, and body mass index have been found to be correlated to the presence of degenerative shoulder abnormalities in this population (Boninger et al., 2001; Lal, 1998).

Although several studies have characterized the presence of shoulder pathologies in adult MWC users, limited data exist for the pediatric population.

Shoulder Biomechanics

Shoulder Kinematics

The shoulder complex is highly mobile. Together, the GH, AC, ST, and SC joints allow movement at the shoulder. As mentioned above, a majority of shoulder movement comes from the GH joint, but scapular movement is also required to reach full ROM. The GH joint allows for up to 120 degrees of elevation while the scapula aids in the remaining one third of total arm elevation. If the ST articulation were fused or if the serratus anterior were paralyzed, the individual would not be able to elevate the shoulder to full ROM. Rotation in the AC and SC joints during elevation and circumduction are also crucial to the rhythmic movement of the shoulder The SC joint allows a maximum of 35-45 degrees of clavicular elevation, which is necessary for scapular movement (Neumann, 2002). Overall, the shoulder is an extremely complex system that requires synchrony between its moving parts. If one or more of the involved joints, muscles, ligaments, or bones is not working properly, this can disrupt function of the entire shoulder.

The shoulder provides gross motor function and contributes to the fine motor control and manipulation needed for many ADLs. Unfortunately, increased ROM past normal limits and repetitive use of the shoulder in strenuous positions can lead to pain, pathology, and dysfunction in the upper extremity (Ballinger et al., 2000; Brose et al., 2008; Gorce & Louis, 2012; Hogaboom et al., 2013; Koontz et al., 2002). Manual wheelchair users may be at a higher risk of these complications because they rely heavily on their shoulders for not only ADLs but for mobility as well (Morrow et al., 2010). The repetitive motions required and the excessive amount of time spent at increased joint angles during wheelchair propulsion may put excess strain on the shoulder (Boninger et al., 1998; Koontz et al., 2002).

Joint kinematics, or the motion of body segments relative to each other, can be recorded using optical motion capture systems. Motion capture involves the use of adjustable markers that either reflect or project light as well as a series of usually 4 to 32 cameras that record the position of the markers in space (Kitagawa & Windsor, 2008). Sensors in the cameras overlap to triangulate the three-dimensional (3-D) position of the markers, and a computer controls the position of the cameras. Markers can either be passive (reflective) or active (generate light source) and are usually supported by a computer software system to replay or manipulate the generated images (Kitagawa & Windsor, 2008). Markers are placed directly on the subject's body and their size and shape are dependent on the subject as well as the camera resolution. The motion capture cameras are often capable of recording marker position at a rate of 30 to 2000 samples per second, and marker configuration can be adjusted based on the needs of the researcher (Kitagawa & Windsor, 2008). Motion capture is often used in the biomechanics industry to identify and track movement of the human body, including to evaluate the upper extremity motion and joint kinematics of MWC users with SCI (Schnorenberg, Slavens, Graf, et al., 2014; Slavens, Schnorenberg, Aurit, Graf, et al., 2015; Slavens, Schnorenberg, Aurit, Tarima, et al., 2015).

Most ADLs only require a small percentage of the shoulder's full ROM (ex. brushing teeth), but some, such as wheelchair propulsion, may keep the shoulder at increased joint angle for longer periods of time (Sonenblum et al., 2012). The active ROM values for the average adult shoulder are 180 degrees of abduction, 180 degrees of flexion, 60 degrees of extension, 140 degrees of horizontal adduction, 70 degrees of internal rotation, and 90 degrees of external rotation (Whelan, 2014). Reaching for items on a high shelf, doing a pushup, washing hair, or scratching the lower back are a few everyday activities that may require maximum shoulder ROM, however, most ADLs do not (Namdari et al., 2012). One study found that the average functional shoulder ROM needed for able-bodied individuals to perform common upper body tasks is about 120 degrees of flexion, 45 degrees of extension, 130 degrees of abduction, 115 degrees of horizontal adduction, 60 degrees of external rotation, and 100 degrees of internal rotation (Namdari et al., 2012). Another study found that able-bodied children ages 9-12 reached maximum joint angles during functional activities like touching their back and reaching overhead. The average shoulder ROM found for this age group during these activities was 47 degrees of extension, 142 degrees of flexion, 55 degrees of abduction, 32 degrees of internal rotation, and 24 degrees of external rotation (Petuskey et al., 2007). Wheelchair users, however, may not fall within these ranges because they rely more heavily on their upper body for mobility tasks and other ADLs. In a typical propulsion cycle the average wheelchair user reaches a maximum 11-24 degrees of flexion, 46-64 degrees of extension, 21-47 degrees of abduction, and 52-91 degrees of internal rotation in the shoulder (Boninger et al., 1998; Koontz et al., 2002). Although MWC users may not exceed maximum shoulder ROM during every phase of wheelchair propulsion, they may be more likely to spend longer periods of time at increased shoulder joint angles than their able-bodied counterparts (Sonenblum et al., 2012).

Wheelchair propulsion patterns may also influence the maximum shoulder angles reached by MWC users (Shimada et al., 1998). Depending on which pattern an individual demonstrates, their shoulders may spend longer periods of time in more detrimental positions (Boninger et al., 2002; Koontz et al., 2009; Shimada et al., 1998). Wheelchair propulsion patterns are recognized as movement patterns that occur during each phase of wheelchair propulsion. The phases of wheelchair propulsion are the propulsive, or push, phase, in which the hand contacts the pushrim, and the recovery phase, in which the hand leaves the pushrim at the end of the stroke. During each of these phases, the wheelchair user positions their upper extremity joints at different angles, following a specific pattern of motion. The patterns may be based on habit or how the user learned to propel their wheelchair. There are four defined and widely accepted wheelchair propulsion patterns: the semicircular patter, the single loop pattern, the double loop pattern, and the arcing pattern (Boninger et al., 2002). The semicircular pattern occurs when the users' hands fall below the hand rim during the recovery phase of propulsion. The single loop pattern occurs when the hands rise above the hand rim during the recovery phase. The double loop pattern is identified as the pattern in which the hands rise above the hand rim, cross over, and drop under the hand rim again during the recovery phase. Lastly, the arcing pattern occurs when the hands follow the path of the pushrim during the recovery phase (Boninger et al., 2002).

The pattern used during propulsion influences the upper extremity kinematics of the MWC user (Shimada et al., 1998). One early study found that individuals who used the semicircular pattern for propulsion experienced larger joint angles for elbow flexion/extension and shoulder abduction/adduction. On the other hand, subjects who used the double loop pattern produced smaller shoulder flexion/extension angles at slow speeds and smaller abduction/adduction shoulder angles at fast speeds (Shimada et al., 1998). Increased joint angles as a result of wheelchair propulsion patterns may lead to tissue degeneration or shoulder pain, especially if the surrounding muscles are weak or if the scapula lacks stability (Boninger et al., 2002; Koontz et al., 2009; Shimada et al., 1998; Walford et al., 2019).

Several studies have looked at the shoulder, elbow, and wrist kinematics of adult manual wheelchair users during wheelchair propulsion, but few have compared these measurements to pediatric groups. Bednarczyk and Sanderson (1994) found that, compared to adults, pediatric MWC users displayed more shoulder extension (33.8 degrees vs 23.2 degrees) and more shoulder abduction (65.6 degrees vs 56.3 degrees) during wheelchair propulsion, but the angular changes over time were the same for both groups (Bednarczyk & Sanderson, 1994). More research is needed to determine if pediatric MWC users exhibit joint angles similar to adults during wheelchair propulsion.

Shoulder Kinetics

Not only do exaggerated joint angles pose potential dangers for MWC users, but excessive upper extremity forces during wheeled mobility may have negative effects as well (Collinger et al., 2010; Mercer et al., 2006; Walford et al., 2019). During mobility tasks, MWC users rely solely on their upper extremities to propel their wheelchairs. Certain factors like speed, wheelchair type, subject weight, level of injury, and rolling surface may further influence these upper extremity forces that are applied during propulsion (Boninger et al., 1999; Gil-Agudo et al., 2010; Koontz et al., 2002). Kinetic data, such as peak forces and moments, taken during wheelchair propulsion provide researchers with valuable information about the effects of mobility tasks on the upper extremity. Kinetic data are often measured using a SmartWheel (OutFront, Mesa, AZ, USA), an electronic pushrim designed to measure the 3-dimensional forces and torques applied by the user during wheelchair propulsion (Cooper, 2009). This device measures the average push forces, length of push, and the propulsion speed throughout the push cycle. This information can be used to optimize propulsion patterns and wheelchair setup to reduce repetitive motions and upper extremity stress (Cooper, 2009).

During wheelchair propulsion, forces are acting on the wrist, elbow, and shoulder joints at varying degrees throughout the push cycle. One study found that pushrim radial forces for adult wheelchair users average between 34 and 39N while tangential pushrim forces average between 66 and 95N (Robertson et al., 1996). This same study found that most vertical reaction forces during propulsion are applied at the shoulder, and higher moments are seen at the shoulder joint when compared to the elbow and wrist (Robertson et al., 1996). In addition, the greatest forces at the shoulder have been observed during the propulsion phase in the inferior direction, anterior direction, and the medial direction (Koontz et al., 2002). Shoulder flexion in the sagittal plane produces the highest moments during wheelchair propulsion, and internal rotation, adduction, and horizontal adduction produce significant moments as well. These forces and moments have been found to increase even more at higher speeds (Koontz et al., 2002).

The forces applied at the upper extremity joints may change based on the user's SCI level, height, body weight, or wheelchair settings. Often experiencing decreased hand function as a result of their injury, those with tetraplegia lack the grip strength needed to properly grasp a wheelchair pushrim. As a result, the tetraplegic population experiences larger adduction moments in the shoulder and larger superior joint forces in the shoulder, elbow, and wrist during wheelchair propulsion (Gil-Agudo et al., 2010). The height and weight of MWC users can also influence pushrim forces. For example, heavier individuals have shown larger pushrim forces during wheelchair propulsion (Boninger et al., 1999). Lastly, average peak forces and moments acting on the upper extremities during wheelchair propulsion may change based on the user's wheelchair settings and the rolling surface. For example, propelling over inclines, curbs, and textured surfaces requires much larger peak shoulder forces (130% increase in some cases) (Nagy et al., 2012).

A high percentage of MWC users experience shoulder pain, most likely as a result of repetitive strain injury, overuse, or trauma to the upper extremities exacerbated by propulsion (Collinger et al., 2010; Mercer et al., 2006; Robertson et al., 1996). Increased pain can significantly affect a wheelchair user's ability to maintain independence and participate in their meaningful and necessary ADLs. The excessive push forces, peak shoulder loads, and moments that occur at the beginning of the push cycle may provide insight as to why wheelchair users are at higher risk of shoulder pain and pathology (Collinger et al., 2010; Mercer et al., 2006).

Ultrasound Diagnostics

Clinical Significance

Ultrasound is often used to diagnose impingement, instability, calcification, and tissue degeneration in the shoulder (Allen, 2008; McCreesh et al., 2016; Read & Perko, 1998). Ultrasound transducers, or probes, are used to apply ultrasound waves to the anatomical structures desired for view. Piezoelectric crystals inside of the transducer generate sound waves at high frequencies and release them in either a phased, linear, or curved linear array. The ultrasound waves reach the desired location, reflect back towards their source, and are used to determine the position of musculoskeletal structures within the body (Hoskins et al., 2010)

Ultrasound Protocol

During an ultrasound procedure, the clinician may take images in multiple planes and along several different axes in order to view the underlying physiological structures more accurately. The clinician may also move the patient or the transducer in different positions throughout the procedure to gather more information about the musculoskeletal anatomy. The transducer is placed along the long axis of a muscle (parallel to the tendon) for the longitudinal view or along the short axis of a muscle (perpendicular to the tendon) for the transverse view. These images can be taken as still images or as a series of images over time (a cine loop) to show the structures from multiple angles (Martinoli, 2010).

In 2010, the European Society of Musculoskeletal Radiology developed a set of technical guidelines and standardized protocols for imaging the shoulder using ultrasound (Martinoli, 2010). These guidelines provide clinicians with a standardized procedure for positioning the ultrasound probe and viewing specific shoulder anatomy. For example, the guidelines recommend that the clinician place the patient’s arm in slight internal rotation with the forearm supinated and the elbow in 90 degrees of flexion to best examine the long head of the biceps tendon. From this position, the clinician can use short and long axis planes to examine the biceps tendon for tears or inflammation (Martinoli, 2010). For examination of the subscapularis tendon, it is recommended that the clinician place the patient in shoulder external rotation with the elbow tight to the abdomen and the forearm supinated. The clinician can then evaluate the subscapularis tendon in the long and short axes while passively rotating the shoulder (Martinoli, 2010). The protocol also suggests that the supraspinatus tendon be imaged from two different positions. The first has the patient positioned with their palm resting on their lower back of the same side. The supraspinatus tendon should be imaged in the short and long axis and can be found by moving the transducer directly superior from the biceps tendon. In this position, the subacromial-subdeltoid bursa can be seen between the deltoid and the supraspinatus. The supraspinatus can also be viewed while the patient places their hand on the opposite side of their lower back with their arm pressed tightly against their chest. This simulates excessive internal rotation at the shoulder and allows the clinician to more easily examine any supraspinatus pathology (Martinoli, 2010). To test for subacromial impingement or bursitis, the protocol informs the clinician to position the patient in about 90 degrees of abduction and internal rotation. From this position, the clinician can access the subacromial bursa by placing the probe in the coronal plane. According to this protocol, the AC joint can also be examined for osteophytes or joint effusion using ultrasound. To view the joint, the transducer should be placed in the coronal plane and moved along the anterior to posterior axis. Even more, the European Society of Musculoskeletal Radiology has guidelines for examination of the posterior GH joint, the infraspinatus and teres minor tendons, and the coracoacromial ligament as well (Martinoli, 2010).

Doppler Sonography

Neovascularization, or the development of new blood vessels following injury, is often seen in patients with rotator cuff tendinopathy (Kardouni et al., 2013). Doppler sonography, which uses color maps to display the speed and direction of blood flow, is often used to identify neovascularization in the body, specifically the shoulder. This technology allows the examiner to identify areas of higher or lesser blood flow, which could indicate tendinopathy or degeneration in the targeted tissues (Strunk et al., 2003).

Pediatric Ultrasound

Ultrasound is often used in adult populations, but clinicians use it to diagnose pathology in children as well. Musculoskeletal ultrasound has been proven to effectively detect synovitis, joint effusion, cartilage degeneration, edema, and arthritis in pediatric groups (Tok et al., 2011). Although shoulder pathologies are less common in children, ultrasound is often used with teenage athletes to evaluate osseous abnormalities in the shoulder and rotator cuff injuries as well (DiPietro & Leschied, 2017). Ultrasound has even been used to treat neonates with posterior shoulder subluxation following brachial plexus injuries and to diagnose glenoid dysphasia in infants and toddlers (DiPietro & Leschied, 2017; Pai & Thapa, 2013).

Similar ultrasound procedures are used to assess both children and adults, but anatomical differences pose challenges for clinicians when evaluating pediatric patients. In general, children have smaller musculoskeletal structures, and therefore, may require alternate ultrasound protocols in some circumstances. For example, because children have thinner tendons, it is recommended that clinicians use passive motion and cine loops to more effectively image pediatric muscles (Bhatnagar, 2018). Ligaments may also be more difficult to view in children because the epiphysis of pediatric bones are more cartilaginous than in adults. On the other hand, neovascularization may be easier to image because children have denser muscles with less connective tissue (Bhatnagar, 2018). Due to these differences between adult and pediatric anatomy, more standardized imaging protocols for the pediatric population may be needed. Although no standard procedures exist for ultrasound assessment of the pediatric shoulder, there are standard protocols for ultrasound imaging of the pediatric knee that could be applied to the upper extremity (Ting et al., 2019).

In some cases, ultrasound has even been proven to be a more superior diagnostic tool for pediatric populations because it is cheap, easy to use bedside, non-invasive, and can be conducted while a child plays or sits on their parent's lap (Tok et al., 2011). Whereas MRI requires the patient to lie still in isolation for long periods of time, ultrasound can provide a more comfortable, less frightening alternative for pediatric diagnostics.

Outcome Measures for Manual Wheelchair Users

Musculoskeletal Pain

Individuals with SCI are extremely likely to experience some level of either chronic or acute pain following their injury. According to the International Association for the Study of Pain, chronic pain is pain that continues past the typical course of recovery, usually 12 weeks, and often persists without the presence of tissue damage (Engel, 2019). It has been reported that up to 94% of adults with SCI experience chronic pain following their injury, 30% of which is identified as neuropathic pain (Calmels et al., 2009; Celik et al., 2012; Defrin et al., 2001).

One of the most prominent forms of pain in MWC users is shoulder pain. Shoulder pain may begin acutely due to tissue degeneration, but often develops into chronic shoulder pain overtime (Alm et al., 2008; Curtis et al., 1995b). Several studies have reported the presence of shoulder pain in adult MWC users to be anywhere from 30-80%, but far fewer studies have been able to quantify pediatric shoulder pain (Alm et al., 2008; Curtin et al., 2017; Ferrero et al., 2015; Sawatzky et al., 2005). In 2019, Schottler et al. measured shoulder pain in pediatric MWC users with SCI. This study found that 26% (6 subjects) of the 23 pediatric subjects tested exhibited shoulder pain at the time of the study (Schottler et al., 2019). Another study looked at the prevalence of shoulder pain in pediatric MWC users with spina bifida. This study found that 16% of participants 10 to 18 years of age reported shoulder pain (Roehrig & Like, 2008). Although limited data exists on the presence of shoulder pain in pediatric MWC users, this population has, however, demonstrated lower prevalence and severity of shoulder pain when compared to adults of similar demographics (Sawatzky et al., 2005).

Finally, the presence of chronic pain experienced by MWC users can be strongly linked to mental health, occupational performance, and quality of life (Ballinger et al., 2000; Pentland & Twomey, 1994a, 1994b; Samuelsson et al., 2004). Those experiencing chronic pain may struggle even more to complete their daily tasks, such as self-care activities, as pain can inhibit movement, motivation, and independence (Samuelsson et al., 2004). Youth with paraplegia are at a higher risk of experiencing these outcomes later in life because they must endure this unique lifestyle for longer periods of time compared to those with adult-onset SCI (Schottler et al., 2019).

Many researchers have explored the relationships between shoulder function, movement, pain, and pathology in MWC users. Because MWC users rely exclusively on their upper extremities for mobility and transfers, they are more at risk of overuse or misuse of their upper extremities, which can lead to pain. One study determined that MWC users with SCI who experienced shoulder pain during weight-bearing transfer tasks were also more likely to have increased scapular upward rotation and greater anterior tilt during these tasks (Nawoczenski et al., 2012). Another study found that, following repeated transfers, the biceps tendons of MWC users that had higher levels of tissue degeneration were also more likely to be in pain (Hogaboom et al., 2013).

In the clinical world, pain can be relatively well-described using two metrics: pain intensity and pain interference. Pain intensity, or pain severity, relates to the patient's level of pain or the strength of the pain that he or she is experiencing. Pain interference defines how much the individual's pain is interfering with or affecting his or her ability to complete ADLs and other daily activities (Engel, 2019). There are many validated tools and assessments that measure self-reported pain intensity and pain interference across different patient groups. Pain intensity is most commonly recorded using a numeric rating scale, the most popular being the 11-point Numeric Rating Scale, which asks patients to rate their pain on a 0 to 10 scale, 0 being no pain and 10 being the worst pain. Pain interference is often recorded on a similar scale, but responses relate to the effects of pain on daily life, such as with household chores, sleep, mood, and social relationships (Engel, 2019). Pain severity may also be recorded on a visual analog scale. A visual analog scale is a line, usually 10 cm long, where each end of the line represents the low and high extremes of the pain measure (Engel, 2019). With a visual analog scale, the patient is asked to mark where along the line they feel their pain levels best fit.

The Patient-Reported Outcomes Measurement Information System (PROMIS) pain forms, Wheelchair Users Shoulder Pain Index (WUSPI), International Spinal Cord Society Pain Basic Data Set (ISCIPBDS), and Brief Pain Inventory are a few of the comprehensive assessments most often used to measure pain in the SCI population (Amtmann et al., 2010; Finley & Euiler, 2019; Gibbs et al., 2019; Giner-Pascual et al., 2011; Stirane et al., 2012). Most often, pain severity and interference are measured using adapted numeric rating scales, but assessments like the WUSPI and the PROMIS have modified assessments for both pain interference and pain behavior scores (Askew et al., 2016b).

The ISCIPBDS (version 2.0) asks the patient to describe his or her pain in the last seven days in terms of how it has interfered with day-to-day activities, overall mood, and ability to get a good night's sleep. Pain interference in these areas is rated on a 0-10 scale, 0 being no interference and 10 being extreme interference. The ISCIPBDS also has the patient identify and describe their three worst pain problems, including the type of pain, its location, and its intensity. The ISCIPBDS is a valid and reliable measure for recording pain in the SCI population (Jensen et al., 2010)

The PROMIS pain assessments consist of several different long and short forms that measure pain interference, pain severity, and pain behaviors. The pain interference scales are most often used, and they exist in 4-item, 6-item, and 8-item versions. Each pain interference form has the patient rate their pain in the past seven days based on how often the pain interfered with physical, mental, and social activities (Chen et al., 2018). The items are rated on a scale from 0-4, 0 being never interfered, and 4 being almost always interfered. The PROMIS pain interference, pain behavior, and pain intensity forms are all reliable and valid assessments for measuring pain (Amtmann et al., 2010; Askew et al., 2016a).

The Wheelchair Users Shoulder Pain Index (WUSPI) is often used with the SCI population because it is the most consistent and the most reliable of the pain indexes, and it was specifically made to evaluate shoulder pain in wheelchair users (Curtis et al., 1995a). In fact, it is the only published measure created solely for the purpose of measuring SCI shoulder pain interference during wheelchair-assisted functional activities. The WUSPI is a 15-item index that utilizes a visual analog scale to measure shoulder pain intensity and the negative effects of that pain on functional activity for MWC users with SCI (Sawatzky et al., 2008). The index addresses a variety of activities, like self-care and mobility, and each of these items targets a functional activity that is unique in the way it produces stress on the shoulder. When it was first developed, the WUSPI found that 73% of subjects tested had shoulder pain, and pain was found to be most intense during activities that required larger shoulder ROM and strength (Curtis et al., 1995b). Functional activities such as propelling on uneven surfaces, washing behind the back, transferring into a bathtub, and lifting objects overhead were found to be some of the most painful activities for this population (Curtis et al., 1995b).

The pain experiences of MWC users may vary depending on their level of injury and type of spinal cord lesion. For example, one study comparing pain in subjects with varying levels of SCI found that subjects with tetraplegia (59%) reported experiencing more intense pain symptoms and more pain in general than subjects with paraplegia (42%) (Curtis, Drysdale, et al., 1999). Similarly, Ferrero et al. (2015) found that those with higher levels of SCI (T2-T7) report more shoulder pain than those with lower levels of SCI (Ferrero et al., 2015).

As mentioned previously, pain associated with SCI and wheelchair use can greatly affect an individual's ability to interact with their environment. Shoulder pain can affect a wheelchair user's ability to reach, lift, transfer, and drive, which may ultimately restrict their independence and participation. Pain can also greatly affect an individual's level of physical activity, mental health, and quality of life. MWC users with SCI who report increased shoulder pain tend to report a lower quality of life and are less likely to engage in physical activity on a regular basis (Stirane et al., 2012).

Independence & Participation

People with disabilities are capable of interacting with their communities and completing meaningful occupations, but pain and loss of function may make it challenging for these individuals to participate in activities as independently as they would like. Functional independence and participation levels are therefore important measures for understanding the effects of disability on daily life. There are several assessments that are used clinically to measure these outcomes in those with disabilities and/or diminishing health, including those with SCI. The Functional Independence Measure, the Craig Handicap Assessment and Reporting Technique, the Barthel Index, and the Spinal Cord Independence Measure (SCIM) are a few of the assessments that have been used to measure independence and participation levels in SCI populations (Kennedy et al., 2006; Osterthun et al., 2020; Roth et al., 1990; Whiteneck et al., 2004).

Of these assessments, the SCIM is unique in that it includes areas of function that are most relevant to the SCI population, excludes abilities that are not often associated with SCI deficits, and weighs certain activities higher that are perceived as more important for this population (Catz et al., 1997). Overall, the SCIM is a reliable and valid disability scale that measures the independence levels of those with SCI in the areas of self-care, respiration and sphincter management, and mobility (Catz et al., 1997). The scale consists of 19 total items, which address areas such as feeding, bathing, dressing, grooming, bladder management, and outdoor mobility. Each item is scored on its own unique scale based on the weight of the activity, with scores ranging from 0 to 15. The self-care category includes 6 items (0-20 total), the respiration and sphincter category includes 4 items (0-40 total), and the mobility category includes 9 items (0-40 total). The highest possible score for the assessment is a 100, which indicates complete independence in all categories (Catz et al., 1997).

Independence and participation outcomes measures are important tools in identifying the effects of pain and disability on daily life for individuals with SCI. For example, MWC users with SCI who have reported experiencing shoulder pain tend to score lower than average on the Craig Handicap Assessment and Reporting Technique, indicating that pain may negatively affect an individual's ability to navigate their environment and participate in their community (Ballinger et al., 2000). Similarly, MWC users with decreased shoulder ROM have been found to have lower FIM scores, signifying that they are less likely to be independent with ADLs and more likely to require assistance with wheelchair propulsion and transfers (Ballinger et al., 2000). The results of these studies imply that shoulder pain and decreased function as a result of SCI may prevent MWC users from independently completing their ADLs. In addition, functional independence with wheelchair mobility has also shown to be a strong indicator for increased levels of community participation. For example, one study determined that MWC users with SCI who were more comfortable with and proficient in standard wheelchair skills were more likely to engage with their communities (Hosseini et al., 2012).

Quality of Life & Satisfaction

Those with SCI are likely to face extreme life changes following the onset of their injuries. These changes can lead to severe physical, psychological, mental, and emotional adjustments for these individuals, all of which, may negatively affect their perceived satisfaction and quality of life (Ataoğlu et al., 2013; Finley & Euiler, 2019; Kennedy et al., 2006; Tate et al., 2002). There are several tools in existence that are frequently used to measure satisfaction and quality of life outcomes. These tools can help to determine an individual's sense of satisfaction and perceived well-being following a disease or injury. To determine the perceived quality of life of MWC users with an SCI, assessments like the Satisfaction with Life Scale (SWLS), Subjective Quality of Life Questionnaire, and the 36-Item Short Form Health Survey are often used (Finley & Euiler, 2019; Mulroy et al., 2016; Stirane et al., 2012; Winkler et al., 2008).

The SWLS is a subjective assessment that measures global life satisfaction, quality of life, and subjective well-being. It consists of 5 items that are scored on a 7-point numeric rating scale, 0 being "strongly disagree" and 7 being "strongly agree." Scores range from 5 to 35, where 35 indicates complete satisfaction (Pavot & Diener, 2008). The SWLS has proven to be a valid and reliable tool for measuring life satisfaction in the SCI population, and scores on the SWLS have shown to correlate with measures of mental health and depression (Pavot & Diener, 2008; Post et al., 2012).

Social integration, disability classification, independence levels, and other demographics, such as relationship status and employment status, are known predictors of health-related quality of life scores for people with SCI (Putzke et al., 2002; Richards et al., 1999; Vogel et al., 1998). Pain, in particular, seems to have a strong inverse relationship with quality of life (Ballinger et al., 2000; Finley & Euiler, 2019; Stirane et al., 2012). Independence with mobility and competency with a manual wheelchair can have also shown to correlate with higher levels of life satisfaction (Hosseini et al., 2012; Putzke et al., 2002). Those who demonstrate a higher proficiency in wheelchair skills and those who report having better access to their environment are more likely to report a higher quality of life (Hosseini et al., 2012;

Richards et al., 1999). Physical activity levels can be a predictor for quality of life and satisfaction as well. In one study, manual wheelchair users who spent more time participating in leisure physical activity reported having higher levels of life satisfaction (Mulroy et al., 2016). Other factors that may affect quality of life include independent living, relationship, and employment statuses. For example, adults with SCI are generally less likely to live independently, drive, and get married when compared to the general population (Vogel et al., 2011; Zebracki et al., 2010). Similarly, although adults with SCI are more likely to receive higher levels of education than their able-bodied counterparts, they are much less likely to be employed than those without a disability (Zebracki et al., 2010). These factors could potentially influence a MWC user's satisfaction with life and self-reported quality of life.

Depression & Anxiety

Coping with the onset of a disability can be a traumatic, life-altering experience. Individuals with SCI must often re-learn how to interact with their environment, and this can be a stressful transition. These abrupt changes in overall health, independence, and functional ability may ultimately influence the mental health of MWC users. It is estimated that anywhere from 20 to 50% of adults with SCI experience depressive symptoms and/or anxiety, with nearly 7% of these individuals experiencing regular suicidal ideation and 3% dealing with major depressive disorder (Anderson et al., 2007; Hancock et al., 1993; Khazaeipour et al., 2015; Lim et al., 2017; Zebracki et al., 2010). Compared to able-bodied individuals of similar demographics, adults with SCI are much more likely to report anxiety and/or depressive symptoms (Hancock et al., 1993; Lim et al., 2017).

Shoulder pain, decreased physical activity due to functional deficits, and a shorter duration of injury have also been linked to higher levels of depression in MWC users (Anderson et al., 2009; Ataoğlu et al., 2013; Mulroy et al., 2016; Wang et al., 2015). In one study, subjects who reported lower daily distances of wheelchair propulsion also reported higher levels of depression (Mulroy et al., 2016). As expected, higher levels of anxiety and depressive symptoms have been correlated to lower quality of life, life satisfaction, and participation outcomes for MWC users with SCI (Anderson et al., 2007).

Outcomes Specific to Pediatric-Onset SCI

Pediatric MWC users with SCI have to overcome unique challenges associated with their disability as they navigate the already difficult transition from childhood to adulthood. Children may be more physically resilient to injuries sustained in childhood, but they are also exposed to associated health risks for longer periods of time (Sawatzky et al., 2005; Zebracki et al., 2010). Although pain, functional independence, and quality of life assessments have been created to specifically gather pediatric outcome measures, fewer options are available, and most do not address all aspects of life for children with SCI (Mulcahey et al., 2016; Mulcahey et al., 2010).

Many adult outcome measures have been adjusted for pediatric use. The Satisfaction with Life Scale has been modified for use with children (SWLS-C). The Spinal Cord Injury Functional Index was modified to create the Pedi-SCI, an assessment that includes both child and parent responses to determine physical functioning of children with SCI (Tian et al., 2014). The PROMIS measures include a pediatric pain interference short and long form for use with children. Even a pediatric version of the Functional Independence Measure, the WeeFIM, was developed for use with children who have disabilities (Msall et al., 1994). Although these assessments have been modified to address pediatric concerns, they are often not comprehensive enough to quantify the full effects of disability on the pediatric SCI population (Kelly et al., 2012; Mulcahey et al., 2016; Mulcahey et al., 2010).

These pediatric assessments do, however, measure outcomes similar to the adult versions. These outcomes, such as pain, independence, participation, physical activity, and life satisfaction, are often strong predictors for overall health-related quality of life. One recent study identified three main parameters for determining the quality of life of children in wheelchairs: participation and positive experiences, self-worth and feeling fulfilled, and health and functioning. (Bray et al., 2017). Other studies have found that perceived health status and independence in mobility are also predictive of health-related quality of life in pediatric groups (Kelly et al., 2012). Each of these parameters has a strong influence on pediatric quality of life in the SCI population.

As mentioned, participation and community engagement can also be extremely influential for pediatric populations with SCI, but most participation outcome measures do not fully assess the aspects of participation most relevant to children with spinal cord injury. Most tools only measure participation in play and leisure activities, and do not include participation in school-specific activities or self-care tasks (Mulcahey et al., 2016). The most comprehensive assessment tool, the Pediatric Measure of Participation (PMoP) was created to address all areas of participation relevant to children with SCI. This measurement tool assesses participation in self-management tasks, like dressing oneself, and participation in school and community activities, like joining a sports team (Mulcahey et al., 2016). This information is valuable for clinicians and researchers because participation frequency and context can help to predict quality of life scores for children with SCI (Kelly et al., 2012). For example, Kelly et al. (2012) found that children ages 6-12 reported higher social, school, and overall quality of life scores if they participated in activities outside of their home, and adolescents ages 13-18 reported higher emotional quality of life scores if they participated in community programs with more diverse groups. Other factors related to SCI may also affect a child's level of participation and integration within their community. Education level, parent income, employment, functional independence, and health status may all play a role in a pediatric wheelchair user's ability to participate in their community (Anderson et al., 2003).

Similar to adults, a child's level of independence, participation, and disability may also affect their mental health. It is has been reported that roughly 13% of children ages 7 to 17 with SCI exhibit severe symptoms of anxiety and 6% exhibit severe levels of depression (Anderson et al., 2009). One study found that children who sustained their SCI more recently or who presented with lower functional independence scores were more likely to exhibit symptoms of anxiety and depression, which also correlated with a lower quality of life (Anderson et al., 2009).

The age of SCI onset may also play a role in an individual's health outcomes. MWC users with pediatric-onset SCI are at risk of serious medical complications and overuse injuries for longer periods of time than those whose injuries occur later in life, which leads to higher morbidity and mortality rates for the pediatric-onset group (Vogel et al., 2011). Adults with pediatric-onset SCI have spent more time in a wheelchair than those with adult-onset. As a result, adults with pediatric-onset are more likely to have pressure ulcers and other health complications than those with adult-onset SCI (Vogel et al., 2011). Despite the longer period of time spent in a wheelchair, however, adults with pediatric-onset SCI have been found to have comparable or even lower levels of shoulder pain than those with adult-onset SCI, which may be due to the fact that the developing skeleton of a child is better equipped to withstand repetitive push forces (Sawatzky et al., 2005; Vogel et al., 2011). There is currently not sufficient evidence of shoulder pain in pediatric manual wheelchair users, but because there is a significant relationship between age and the onset of shoulder pain, more research is needed to preserve the shoulder integrity of pediatric manual wheelchair users as they enter adulthood (Ferrero et al., 2015). Like shoulder pain, the independence levels of individuals with SCI may also change across the lifespan. For example, one study compared the SCIM III scores of adolescents (ages 13-17) and adults with cervical SCI and found that the adolescent group reported significantly higher SCIM scores and higher gains in SCIM scores over time than the adult group (Geuther et al., 2019). These results may indicate that, when compared to adults, adolescents with SCI can make more functional independence gains following their injury (Geuther et al., 2019). Another study that compared the SCIM independence scores of multiple age groups found that mobility independence was negatively associated with age for manual wheelchair users with SCI (Hinrichs et al., 2016). In this study, the odds of a participant being independent decreased with age in all mobility domains, and the age group with the highest percentage of reported independence was the youngest (16-30 years) (Hinrichs et al., 2016).

Those who receive their spinal cord injuries at a young age may also face unique challenges as they approach developmental milestones throughout puberty, adolescence, and young adulthood. For example, living with a SCI and using a manual wheelchair can impact an individual's ability to build romantic relationships and engage in sexual intimacy with a partner, which can affect emotional development and quality of life (Vogel et al., 2014; Zebracki et al., 2010). Those with pediatric-onset SCI who report being married or engaged in an intimate relationship are more likely to have higher levels of quality of life and life satisfaction (Zebracki et al., 2010).

The coping strategies that adolescents develop following their SCI also play an important role in their recovery. A large percentage of adults with pediatric-onset SCI report using positive coping strategies, such as acceptance, positive reframing, emotional support, humor, and religion to deal with their injury, however, many adults report using behavioral disengagement and illegal substances as well (Anderson et al., 2008). These coping strategies and behaviors may be learned at a young age, making it more difficult for those with pediatric-onset SCI to break from these negative habits. As a result, an SCI at an early age may amplify the risks of substance abuse in following years. Risk-taking behaviors naturally elevate in young adulthood as adolescents begin to challenge the boundaries of their independence. Individuals with pediatric-onset SCI may be more at risk of substance abuse because they may use illegal substances as a way to cope with their injury (Anderson et al., 2008; Zebracki et al., 2010).

Proper Wheelchair Setup & Effects of Fit

Wheelchair Setup

A manual wheelchair can be configured many different ways to meet the needs of the user. Most manual wheelchair setups include two large rear wheels, two front caster wheels, a backrest, and footrests. Some wheelchairs may also have armrests, headrests, trunk supports, or leg supports depending on the user's needs. Wheelchair systems may be further customized with different types of seat cushions, various pushrim textures or grips, and different tire thicknesses.

To propel their wheelchairs, MWC users grasp the pushrims along the circumference of the rear wheels. These rear wheels vary in diameter and may be positioned farther forward or farther backward depending on the needs of the MWC user. The position of the wheel axle in this horizontal axis is called the fore-aft position while the position of the wheel axle in the vertical axis is called the vertical position (Boninger et al., 2000) (Chapter III, pp. 76, Figure 11). The angle of the rear wheels may also be adjusted. They may run parallel to each other in the sagittal plane or they may slope slightly outward, creating a camber angle. A larger camber angle will widen the wheelchair's base of support, but this may make it more difficult for the MWC user to maneuver around corners and narrow spaces (Tsai et al., 2012; Veeger et al., 1989). Similar to the rear wheels, the smaller caster wheels may also be positioned farther forward, farther backward, or farther apart to adjust the stability of the wheelchair system (Kirby et al., 1992).

The wheelchair seat, backrest, and footrest parameters are often set up to meet the needs of the specific MWC user. For example, the seat of a manual wheelchair will either run parallel to the floor at a straight angle or be sloped up slightly in the front at an acute inclined angle (Giner-Pascual et al., 2011). This parameter is called the seat sagittal angle or dump angle (Chapter III, pp. 77, Figure 12). Often times those with a higher level SCI will require a larger dump angle to facilitate better sitting posture (Cloud et al., 2017). The seat height is the distance from the floor to the seat and the seat width is the distance from the left edge of the seat to the right edge of the seat (Waugh & Crane, 2013). The seat height and width are dependent on the MWC users' height, hip width, arm length, and rear wheel diameter. The backrest height, or distance from the seat to the top of the backrest, will also vary depending on the MWC users height, level of impairment, and preferences (Waugh & Crane, 2013). The backrest may be set perpendicularly to the seat or the seat to backrest angle may be slightly larger to adjust the sitting posture of the MWC user. Lastly, the footrests may be positioned differently depending on the size and needs of the MWC user. The footrest length, or distance from the front of the seat to the back of the footrest, will depend on the length of the MWC users lower leg, and the angle of the footrest in relation to the floor may be adjusted as well (Waugh & Crane, 2013).

Wheelchair Fit

To ensure that MWC users are maintaining the safety of their joints and propelling most efficiently and comfortably, the dimensions and features of the wheelchair may be adjusted to best fit the user. Wheelchair fit is usually determined by how well the wheelchair matches the anthropometric (height, weight, etc.) measurements and functional needs of the MWC user. As mentioned above, the fit of the wheelchair may change if the axle, seat, and footrest positions do not match the user's elbow, shoulder, hip, upper leg, or lower leg measurements.

Although many wheelchairs are customizable, it is thought that up to 68% of wheelchairs are not properly fitted to their users (Medola et al., 2014). An ill-fitted wheelchair that has not been adjusted to its user's preferences, physical needs, and functional requirements can create a variety of problems for that individual (Chaves et al., 2004). An inappropriate wheelchair can limit an individual's functional independence, comfort, participation, and overall quality of life, which is why it is extremely important that a manual wheelchair fit the specific needs of the individual using it (Chaves et al., 2004; Di Marco et al., 2003). In fact, 41% of MWC user-reported issues stem from the physical features of the device and their lack of conformity to the user (Mann et al., 1996). One study found that only 12 of 30 participants were satisfied with their existing wheelchair seating position, indicating that up to 60% of MWC users with SCI are currently using non-preferred wheelchair setups (Alm et al., 2003). For pediatric MWC users, wheelchair fittings can be particularly challenging. Oftentimes, health insurance companies will only pay for a new wheelchair every 3-5 years, so pediatric wheelchairs must be fitted to allow for rapid growth of the child (Krey, 2005).

If a wheelchair is too heavy, too large, too wide, or lacking support, it can create frustration and discomfort for the user. By changing a wheelchair's design and adjusting its parameters to meet the specific needs of each MWC user, it may be possible to improve the efficiency of wheelchair propulsion, increase stability, and decrease pain and discomfort for the individual (Medola et al., 2014). Aside from wheelchair configuration, the quality of the wheelchair may also be a factor in user satisfaction. For example, ultralightweight wheelchairs allow for more efficient mobility than lightweight wheelchairs due to their higher quality and decreased weight (Oyster et al., 2011).

Effects of Wheelchair Fit on Outcomes

The relative fit of a wheelchair can greatly affect a user's social participation, health, and quality of life (Winkler et al., 2008). Individuals who receive better quality, adjustable manual wheelchairs are less likely to feel limited in their roles due to emotional distress and are more likely to have better social functioning and general health (Winkler et al., 2008). An ill-fitting wheelchair may also make wheelchair propulsion more difficult or dangerous for the MWC user by exposing their upper extremities to increased forces or joint angles. This in turn may lead to worsened propulsion efficiency, increased risk of pathology, or heightened pain (Boninger et al., 2000; Giner-Pascual et al., 2011). Overall, a good wheelchair fit is crucial to facilitating safe, comfortable, and independent mobility for MWC users with SCI.

There are many parameters that can be adjusted to create an ideal wheelchair fit, but axle position and seat position may be the most influential. The vertical and horizontal axle position of the rear wheels in relation to the user's upper extremity have been found to effect propulsion efficiency and pathology in MWC users with SCI (Boninger et al., 2000; Cowan et al., 2009; Freixes et al., 2010). Boninger et al. (2000) found that axle position was significantly correlated with frequency of propulsion and upper extremity push angles, parameters known to increase the risk of median nerve injuries. The study determined that shorter vertical distances between the shoulder and the axle and a more forward axle position resulted in better propulsion biomechanics for MWC users with SCI (Boninger et al., 2000). Other studies have found similar results, indicating that an up and forward axle position is most effective in reducing peak forces during wheelchair propulsion (Cowan et al., 2009; Freixes et al., 2010). The seat position will also affect how the MWC user's shoulders and elbows align with the wheel axle. Vertical movement of the seat will alter the MWC users elbow angle when they come in contact with the pushrim, while horizontal movement of the seat will alter the shoulder angle (Kotajarvi et al., 2004). The relationship between the MWC user and the pushrim is dependent on the seat position relative to the wheel. An optimal distance between the axle and shoulder, which can be accomplished by adjusting the seat position, has been found to result in greater propulsion efficiency, smaller joint angles, improved push time, decreased axial and radial forces, greater push duration, and less oxygen consumption in adult MWC users (Gorce & Louis, 2012; Kotajarvi et al., 2004; Van der Woude et al., 1989). Similarly, adjusting the seat height and/or vertical axle position will affect the MWC user's elbow flexion angle when their hands are on the pushrim. If the elbow flexion angle is too large, a higher stroke frequency must be used, but if the elbow flexion angle is too small, more shoulder abduction must be used for propulsion, resulting in an increased risk of shoulder impingement (Boninger et al., 2000; Hughes et al., 1992; Van der Woude et al., 1989).

Another important wheelchair parameter that may affect posture, propulsion efficiency, and the prevalence of shoulder pain in MWC users is the sagittal seat angle, or dump angle. As mentioned previously, the seat may be parallel to the floor or positioned at an incline with the front of the seat slightly higher than the back of the seat. One study found that roughly 56% of the participants used a straight seat angle and 44% used an acute seat angle on their manual wheelchairs (Giner-Pascual et al., 2011). Of these subjects, those who used a straight seat angle were almost twice as likely to have shoulder pathologies and to complain of shoulder pain than those who used acute seat angles. These results indicate that the use of a seat parallel to the ground is a risk factor for shoulder pain and injury when compared to seat angles of 10 degrees or more (Giner-Pascual et al., 2011). An acute seat angle has also shown to reduce lordosis in the posture of MWC users with lower SCI lesions and increase scapulothoracic internal rotation in those with higher SCI lesions (Cloud et al., 2017).

Overall, the way that a MWC user interacts with their wheelchair is dependent on a variety of parameters and settings. Besides those previously mentioned, other parameters, such as wheel diameter, wheelchair mass, wheel thickness, camber angle, caster position, backrest thickness, and backrest height may also influence the efficiency and long-term effects of wheelchair propulsion (Cowan et al., 2009; Kirby et al., 1992; Mason et al., 2012; Sagawa Jr et al., 2010; Tsai et al., 2012; Van Der Linden et al., 1996; Yang et al., 2012; Yoo, 2015). Several studies have investigated the effects of these different parameters on adults with SCI, but few have explored the consequences of wheelchair fit on pediatric outcomes (Krey & Calhoun, 2004). Further research is needed to determine if wheelchair setup variables effect pediatric MWC users with SCI in ways similar to adult groups.

Clinical Guidelines & Recommendations for Wheelchair Use

The wheelchair parameters and settings needed to create the best fit will change depending on the needs, preferences, and limitations of the MWC user. There are, however, several clinical guidelines and recommendations currently in place that help to generally reduce the forces, joint angles, and discomfort experienced by MWC users during propulsion. To decrease the risks of shoulder injury in particular it is recommended that MWC users improve their propulsion biomechanics and use a properly configured wheelchair of higher quality, lower weight, and efficient design (Krey & Calhoun, 2004; Paralyzed Veterans of America Consortium for Spinal Cord, 2005). A properly configured wheelchair will reduce the chances of shoulder strain, injury, and overuse (Krey & Calhoun, 2004).

There are two types of manual wheelchairs that are commonly prescribed: the high strength lightweight K0004 or the ultra-lightweight K0005 (Michael et al., 2020). Although the K0004 is more durable, the K0005 is recommended for long term use with the SCI population because it is the lightest possible chair that allows a custom fit (Michael et al., 2020) Lighter wheelchairs are recommended because they require less force to propel, are adjustable, and are often made with higher quality components (Paralyzed Veterans of America Consortium for Spinal Cord, 2005). With the K0005, the clinician is also able optimize the wheelchair by adjusting its horizontal and vertical rear axle position as well as its camber angle (Michael et al., 2020). This is not possible with the K0004 models.

Clinicians may recommend certain adjustments to manual wheelchairs, such as axle position, cushion type, and backrest shape depending on the needs of the user. Based on reasons stated in previous sections, clinical guidelines recommend that the rear wheel be positioned as far forward as possible while still maintaining stability, and that the seat be vertically adjusted so that the user's elbow angle, or angle between the upper arm and forearm, is between 100-120 degrees when the hand is positioned at top-dead center of the pushrim (Krey & Calhoun, 2004; Michael et al., 2020; Paralyzed Veterans of America Consortium for Spinal Cord, 2005; Slowik & Neptune, 2013). This position eliminates stress on the shoulder and allows for optimal grasp on the pushrim for propulsion. Unfortunately, a forward axle position decreases stability, so wheelchairs are often not delivered in this optimal position (Paralyzed Veterans of America Consortium for Spinal Cord, 2005). Similarly, the lateral position of the rear wheels can affect upper extremity positioning during wheelchair propulsion. Clinicians may recommend a narrower frame because if the wheelchair is too wide, the MWC user may struggle to propel without abducting and elevating the shoulders (Krey & Calhoun, 2004). When recommending seat cushions for MWC users, clinicians must consider the pressure distribution, postural support, maintenance, temperature regulation, weight, airflow, durability, and ease of cleaning (Krey & Calhoun, 2004; Michael et al., 2020). The ideal cushion will allow maximal function, support, and comfort without increasing the risks of skin breakdown. Lastly, clinicians recommend that the backrests of manual wheelchair be adjusted to meet the needs and anthropometric measurements of the MWC user. An optimal backrest is comfortable, minimizes trunk motion, and provides support during wheelchair propulsion without restricting upper extremity movement (Michael et al., 2020).

There are also clinical guidelines in place for proper wheelchair propulsion and functional mobility techniques in adults. It is recommended that MWC users employ the semicircular propulsion pattern when possible because this pattern is associated with lower stroke frequency, decreased joint velocity, and increased propulsion efficiency (Boninger et al., 2002; Krey & Calhoun, 2004). The Paralyzed Veterans of American Consortium for Spinal Cord created a set of clinical practice guidelines for health-care professionals to assist their SCI patients with maintaining their upper extremity limb function. These guidelines recommend that MWC users minimize the frequency of repetitive tasks, minimize the force used during functional tasks, minimize extreme joint position, avoid positioning the hand above the shoulder during propulsion, and avoid excessive internal rotation and abduction (Paralyzed Veterans of America Consortium for Spinal Cord, 2005). It is recommended that MWC users achieve this by using long, smooth strokes that limit forces on the pushrim, allow the hand to stay below the pushrim when not actively pushing, and avoid positions of impingement. All of these guidelines have been shown to reduce the MWC users risks of upper extremity injury and pain in adults (Paralyzed Veterans of America Consortium for Spinal Cord, 2005).

Unfortunately, there are currently no clinical guidelines that comprehensively address wheelchair seating and positioning recommendations specific to the pediatric population (Krey & Calhoun, 2004). Pediatric clinicians often follow the “2 inch rule” by adding 2 inches to the patient's seat width and subtracting 2 inches from the patient's seat depth, but there is limited research to support these recommendations (Krey, 2005) Similarly, Krey (2005) suggests that the pediatric wheelchair axle be positioned under the child's pelvis to distribute body weight and the backrest be high enough to provide trunk control, but not all pediatric clinicians follow these guidelines (Krey, 2005). Looking forward, it is crucial that more research be conducted in this area because, unlike adults, pediatric MWC users with SCI use their wheelchairs for longer periods of time and face unique challenges to wheelchair configuration and fit as they grow. Because pediatric MWC users will be in a wheelchair for the majority of their lives, it is imperative that the wheelchair be optimally configured to reduce overuse and degeneration in the upper limbs (Krey & Calhoun, 2004). This is challenging, however, because children grow and develop so quickly that even the most adjustable wheelchairs often cannot achieve the optimal wheelchair setup for the child. Usually the axle cannot be brought forward enough, the seat cannot be positioned rearward enough, or the seat width does not provide enough adjustability to accommodate for the child's rapid growth (Krey & Calhoun, 2004).

III. Manuscript

Introduction

In the United States, an estimated 125,000 individuals under the age of 21 use a wheelchair for functional mobility, including an estimated 60,000 children with spinal cord injury (SCI) (Brault, 2012; Hanks et al., 2021). Although manual wheelchairs (MWC) can provide children with crucial access to play, education, peer interactions, and independence, wheeled mobility can negatively affect this population as well. A wheelchair not properly fitted to an individual can greatly influence his or her social participation, health, and quality of life (Chaves et al., 2004; Di Marco et al., 2003; Winkler et al., 2008). In addition, a wheelchair not properly suited to the user's needs, preferences, and physical limitations may result in the use of inefficient and potentially harmful wheelchair propulsion mechanics.

Several studies in adults have found that wheelchair parameters, such as the seat angle and the axle position, can negatively impact the efficiency and long-term effects of wheelchair propulsion(Boninger et al., 2001; Giner-Pascual et al., 2011; Kotajarvi et al., 2004; Krey & Calhoun, 2004; Van der Woude et al., 2009). Horizontal and vertical axle positions have shown to affect propulsion efficiency and pathology in MWC users with SCI (Boninger et al., 2000; Cowan et al., 2009; Freixes et al., 2010). Boninger et al. (2000) found that axle position was significantly correlated with frequency of propulsion and upper extremity push angles, parameters known to increase the risk of median nerve injuries. This study determined that a more rearward axle position resulted in more harmful propulsion biomechanics for MWC users with SCI (Boninger et al., 2000). Other studies have found similar results, indicating that an up and forward axle position is most effective in reducing peak forces during wheelchair propulsion (Cowan et al., 2009; Freixes et al., 2010). Similarly, an optimal vertical axle position has been found to result in greater propulsion efficiency, smaller joint angles, improved push time, decreased axial and radial forces, greater push duration, and less oxygen consumption in adult MWC users (Gorce & Louis, 2012; Kotajarvi et al., 2004; Van der Woude et al., 1989). If the vertical axle position is too far below the seat, this will result in a higher stroke frequency, but if the axle is positioned too high, more shoulder abduction is necessary for propulsion, both of which can increase the risk of shoulder impingement (Boninger et al., 2000; Hughes et al., 1992; Van der Woude et al., 1989). Finally, sagittal seat angle has also shown to correlate with the prevalence of shoulder pain and pathology in MWC users (Giner-Pascual et al., 2011). One study found that MWC users who used a straight seat angle were almost twice as likely to have shoulder pathologies and to complain of shoulder pain than those who used an acute seat angle. These results indicate that the use of a seat parallel to the ground is a risk factor for shoulder pain and injury when compared to seat angles of 10 degrees or more (Giner-Pascual et al., 2011). Unfortunately, the effects of wheelchair setup on the pediatric population remain understudied.

This study aims to explore the seat angles and axle positions that are currently being used by pediatric MWC users with SCI and to determine if the relative fit of the pediatric wheelchair is related to pain, pathology, or independence outcomes in children with SCI. It was hypothesized that pediatric MWC users would exhibit differences in wheelchair setup compared to adult recommendations, and that this would correlate with increased supraspinatus tendon pathology, increased shoulder pain, and decreased levels of independence. Outcomes of this research will help inform clinicians when prescribing wheelchairs to children with SCI or when making wheelchair setup recommendations to pediatric MWC users and their families.

Methods

Subjects

Subjects were primary MWC users with SCI who were at an age where they would be eligible to receive school-based occupational therapy services. To be eligible for inclusion in this study, participants needed to meet the following criteria: be an English-speaker, be at least one-year post-injury, have an SCI below the cervical spinal level, and be at an age where they would be eligible to receive school-based occupational therapy services (services start at the age of 3 and are offered through the academic year that the student turns 21 years old). Subjects were excluded from the study if they had undergone an orthopedic surgery in the last year, if they presented with upper extremity joint contractures, or if they had been diagnosed with any other neurological conditions besides SCI. Data were collected at the Shriners Hospitals for Children – Chicago. The study protocol and procedures were approved by the UWM Institutional Review Board. In order to participate in this study, subjects over the age of 12 provided written informed consent and minors below the age of 12 with their parent or guardian provided written informed assent prior to data collection.

Data Collection

Anthropometric measurements, musculoskeletal clinical special tests, outcomes assessments, and ultrasound diagnostics were completed and recorded prior to biomechanical data collection. Subject measurements included height, weight, length of upper extremity body segments, and joint circumference measurements. The subject’s wheel size, age, gender, date of injury, ASIA score, SCI lesion level, and mobility device use history were also recorded (Chapter III, pp. 85, Table 1).

Pain & Independence. Pain outcomes were collected using the Wheelchair Users Shoulder Pain Index (WUSPI) (Figure 3) and the Patient-Reported Outcomes Measurement Information System (PROMIS) pediatric pain interference short form.

WHEELCHAIR USERS SHOULDER PAIN INDEX

Place an "**X**" on the scale to estimate your level of pain with the following activities. Check box at right if the activity was not performed **in the past week.**
Based on your experiences in the past week, how much shoulder pain do you experience when:

		not performed
1. transferring from a bed to a wheelchair?	No Pain [ ]____________X____________Worst Pain Ever Experienced	[ ]

Figure 3: Item 1 on the Wheelchair Users Shoulder Pain Index (WUSPI) showing how the 10cm visual analog scale was used to gather shoulder pain intensities for different ADLs.

The WUSPI was chosen as the main pain outcome because it is a reliable and valid method for measuring shoulder pain intensity and shoulder pain interference for manual wheelchair users with SCI. Additionally, the PROMIS was included as this measure has been validated in children (Curtis et al., 1995a). Pediatric independence and participation levels were also recorded using the Spinal Cord Independence Measure-Third Edition (SCIM-III) (Figure 4).

SCIM-SPINAL CORD INDEPENDENCE MEASURE

Self-Care

1. Feeding (cutting, opening containers, pouring, bringing food to mouth, holding cup with fluid)

0. Needs parenteral, gastrostomy, or fully assisted oral feeding
1. Needs partial assistance for eating and/or drinking, or for wearing adaptive devices
2. Eats independently; needs adaptive devices or assistance only for cutting food and/or pouring and/or opening containers
3. Eats and drinks independently; does not require assistance or adaptive devices

Figure 4: Item 1 on the Spinal Cord Independence Measure -Third Edition (SCIM-III) showing how the questionnaire was used to gather independence scores for different ADLs.

The SCIM was selected because it is a reliable and valid disability scale used to measure the independence levels of children with SCI in the areas of self-care, respiration and sphincter management, and mobility (Catz et al., 1997). All outcomes were completed by participants either in person or in the form of an online survey created using Qualtrics software (Qualtrics XM Platform, Seattle, WA). Copies of the WUSPI, PROMIS, and SCIM-III forms are included in Appendices A-D.

Pathology. A physician identified potential shoulder pathologies using provocative clinical special tests as part of a standard orthopaedic upper extremity exam, and any shoulder abnormalities were then verified with ultrasound imaging. Clinical special tests included the Empty Can, Neer's, Hawkins-Kennedy, the AC joint compression, anterior and posterior apprehension, sulcus sign, Gagney's hyperabduction sign, and Speeds tests. Clinician instructions for each test are included in Appendix E along with the other protocols and checklists that were used during data collection. Following the clinical exam, the same physician administered diagnostic ultrasound imaging of the subject's shoulders using the standardized procedures outlined by the European Society of Musculoskeletal Radiology (ESMR) (Martinoli, 2010; McCreesh et al., 2016). The ESMR guidelines for capturing images of the supraspinatus tendon are also included in Appendix E. One cine loop (i.e., video) and two still images of each tendon were collected in each of the following positions: cross-sectional/short axis, longitudinal axis, and muscle cross-sectional area. The physician used the ultrasound images to identify presence of pathology in the biceps, supraspinatus, and infraspinatus tendons, AC joint effusion and osteophytes, and subacromial bursitis.

Static Wheelchair Settings. Following ultrasound, static images of the subject's manual wheelchair were taken at a frequency of 120Hz, using a 14-camera Vicon optical motion analysis system (Vicon Motion Systems, Oxford, UK) to capture the subject's wheelchair setup

(Figure 5). Eleven 14 mm reflective markers were placed at the borders of the wheelchair seat, top edges of the backrest, ends of the seat frame, and on both wheel axles (Figure 6). Wheelchair measurements gathered from these images included seat sagittal angle, backrest height, backrest width, seat height, seat depth, seat width, wheelchair width, and seat to backrest angle (Figure 7).

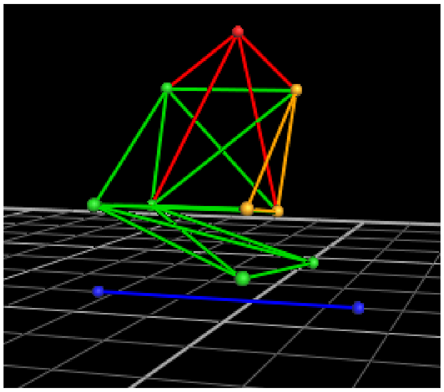


Figure 5: Rendering of manual wheelchair setup using Vicon software after application of reflective markers.

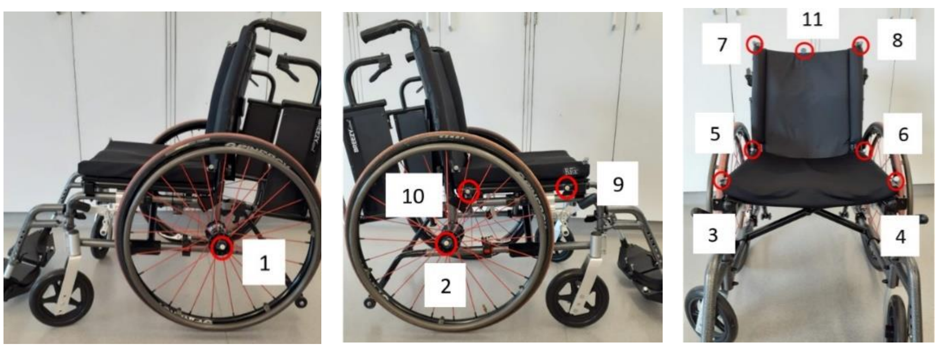


Figure 6: Reflective markers were placed on the 1) left axle, 2) right axle, 3) front right seat, 4) front left seat, 5) back right seat, 6) back left seat, 7) top right backrest, 8) top left backrest, 9) front seat frame, 10) back seat frame, and 11) top middle back rest

Figure 7: Reflective markers positioned on the wheelchair were then used to find the 1) seat depth, 2) seat width, 3) seat height, 4) backrest height, 5) backrest width, 6) seat sagittal angle, 7) seat to backrest angle, and 8) wheelchair width (distance between left and right axle)

Static images were then taken of the subject seated in their wheelchair to gather information about the wheelchair fit relative to the pediatric user (Figure 8). The existing reflective markers remained on the wheelchair and 27 more were added to the bony landmarks of the subject's upper body. Markers were placed bilaterally on the left and right acromion processes, lateral epicondyles, humeri, olecranon processes, ulnar styloids, and third metacarpal-phalangeal joints among other bony landmarks (Figure 9). Subjects were asked to sit back and upright in their chair as naturally as possible and to grasp their pushrims, aligning the markers on their 3rd metacarpal joints with top-dead center of the wheels (Figure 10). Subjects were prompted to keep their arms adducted inwards, in line with the plane of the wheel. To simulate goniometric measurement of the elbow angle in seated position, the markers at the acromion process, olecranon process, and ulnar styloid were used to determine the sagittal elbow angle on the subject’s dominant side when their hands were at top-dead center of the hand rim.

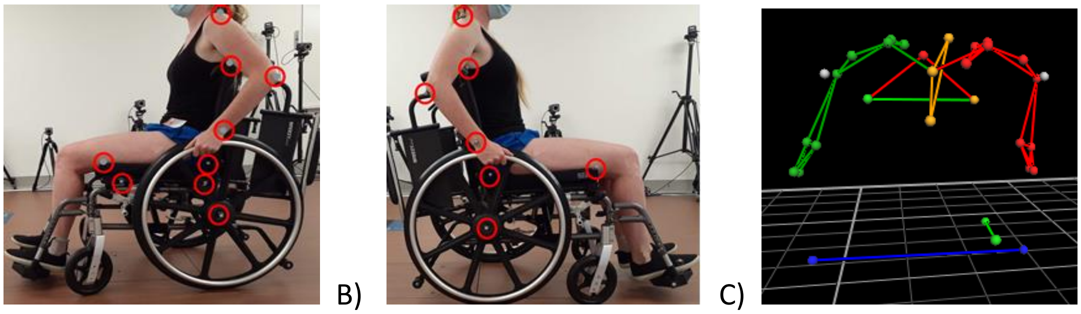
A)  B) C)

Figure 8: A) Left-side view of the participant seated in their wheelchair after being fitted with the reflective markers. B) Right-side view of the participant seated in their wheelchair with the reflective markers. C) Vicon image of a participant seated in their wheelchair.

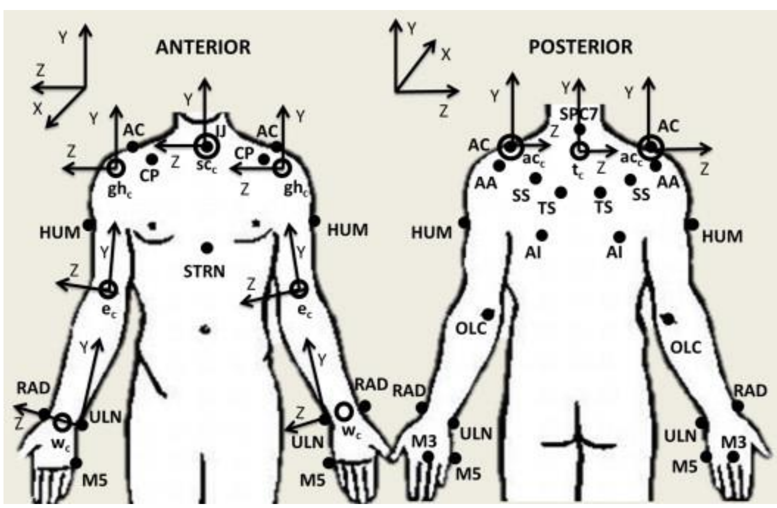


Figure 9: A total of 27 reflective markers were placed on the subject’s upper extremity at the bony landmarks previously established (Schnorenberg, Slavens, Wang, et al., 2014).

Figure 10: The subject was asked to position their dominant hand at top dead center of their pushrim, so that the reflective marker on their third metacarpal joint aligned with the axle marker, making a perpendicular line with the floor.

Dynamic Wheelchair Settings. Finally, reflective markers on the wheelchair were removed, except for the axle markers, and kinematic data were captured during wheelchair propulsion. Subjects affixed with markers propelled their wheelchairs with a SmartWheel instrumented handrim (Out Front, Mesa, AZ) replacing the wheel on the dominant side at a self-selected speed across a level tile floor for a minimum of ten propulsion cycles. Vicon motion capture images were taken at a frequency of 120Hz during wheelchair propulsion to record changes in marker positioning. The markers on the acromion processes and wheel axles were used to determine the fore-aft (XPOS) or horizontal position of the dominant shoulder relative to the wheelchair axle on that side (Figure 11) (Kwarciak et al., 2009).

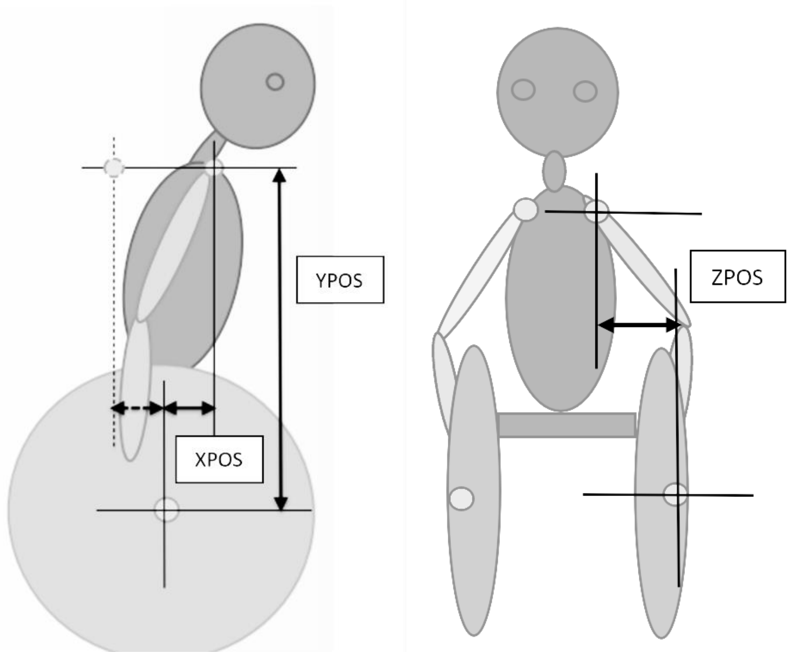


Figure 11: Wheelchair axles can be positioned in front of or behind the user's shoulder in the horizontal plane (XPOS), upward or downward in the vertical plane (YPOS), or adjusted laterally to widen or narrow the space between the wheels and the shoulder (ZPOS) (Schnorenberg et al., 2017).

Data Analysis

Data were analyzed and reported using Vicon motion capture software, MATLAB software (Mathworks, Inc., Massachusetts, USA), Microsoft Excel (Microsoft, Redmond, VA), and SPSS software (SPSS Inc., Chicago, IL). The upper extremity inverse dynamics model developed by Schnorenberg et al. (2014) was used to label upper extremity and wheelchair markers in Vicon for use in calculating joint angles and wheelchair parameters (Schnorenberg, Slavens, Wang, et al., 2014). Vertical and horizontal axle positions, as well as pathology data, were collected and analyzed on each subject's dominant side as it likely that the dominant limb is the primary limb for performing other activities of daily living (ADLs) and instrumental activities of daily living (IADLs) and would, therefore, be more associated with any pain or pathology. Although subjects were asked to propel their wheelchairs for a minimum of ten stroke cycles, the number of propulsion cycles analyzed for each subject varied due to limitations encountered during data collection.

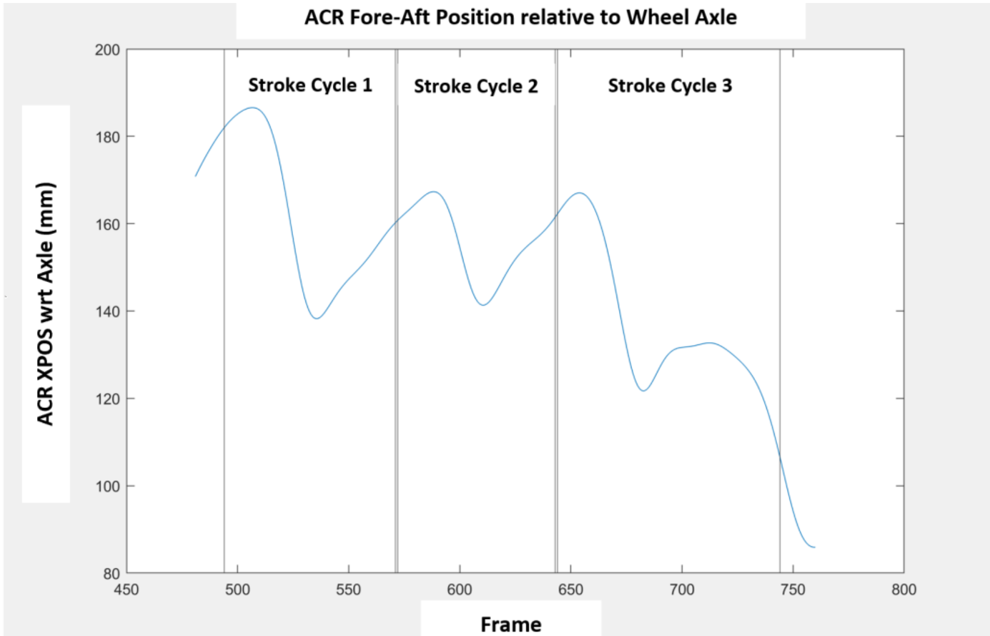
Seat Angle. Seat sagittal angles, or dump angles, were determined by finding the angle between the markers on the front and back of the seat frame relative to horizontal (see Equation 1 in Appendix F). For wheelchair classification in Aim 1, the seat angles were characterized as either straight (seat parallel to the ground) or acute (Giner-Pascual et al., 2011) (Figure 12). The seat to backrest angle, seat height, wheelchair width, and backrest height were also calculated by finding the distances between the relevant markers (see Equations 2-5 in Appendix F). The Matlab code used to calculate these wheelchair measurements as well as the wheelchair fit relative to the participant are included in Appendix G.

A)  B) 

Figure 12: A) A straight seat angle parallel with the floor B) A acute seat angle at about 10 degrees of elevation (Giner-Pascual et al., 2011).

Horizontal Axle Position. Horizontal axle positions in relation to the shoulder were determined using the Vicon software and reflective markers placed on the acromion process and wheel axle on the participant's dominant side. Motion capture data were collected while subjects propelled their wheelchairs at a self-selected speed for a minimum of 10 stroke cycles per subject, and the distance between the shoulder and the axle markers in the horizontal direction were recorded (Boninger et al., 2000). Stroke cycles were defined as beginning with initial contact of the handrim. The horizontal axle position (fore-aft) was determined by subtracting the XPOS of the wheel axle marker from the XPOS of the acromion process. The direction of each value was dependent on the position of the axle relative to the shoulder. For example, the acromion marker (ACR) XPOS value was more positive if the axle was positioned posterior to the shoulder, but if the axle was anterior to the shoulder, the ACR XPOS was negative (Figure 13) (Boninger et al., 2000). The average and standard deviation of the horizontal position of the shoulder on the dominant side relative to the wheel axle was calculated for each stroke cycle and averaged over all the cycles recorded for each subject. Similarly, the average and standard deviation of the maximum horizontal distance between the acromion and the wheel axle on the dominant side were calculated for all stroke cycles for each participant as well.

A)



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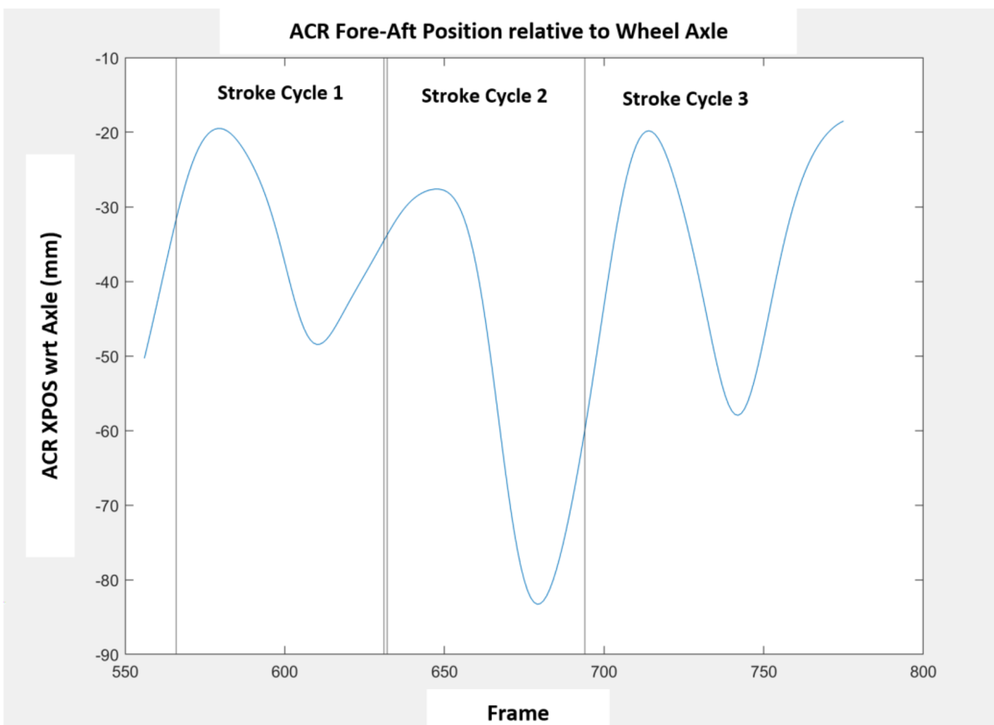


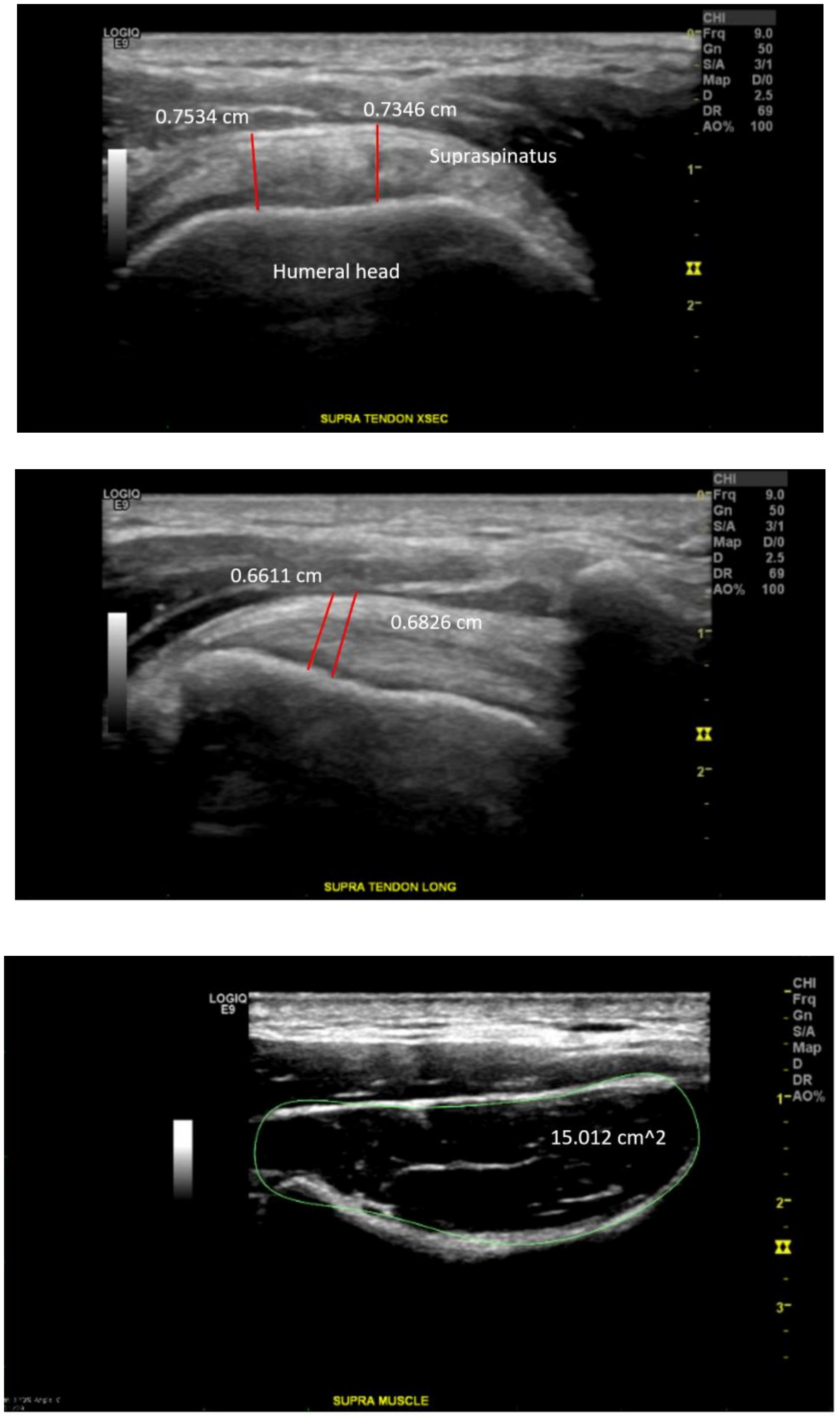
Figure 13: A) Graph showing the acromion (ACR) fore-aft position (XPOS) relative to the wheel axle for a participant with a rearward axle position (positive ACR XPOS). B) Graph showing the ACR fore-aft position relative to the wheel axle for a participant with a forward axle position (negative ACR XPOS).

Vertical Axle Position. The vertical axle position relative to the seat was determined by finding the subject's elbow flexion angle. The elbow flexion angle, or angle between the upper arm and forearm during static sitting, was determined by finding the planar angle between the acromion process, olecranon process, and ulnar styloid on the dominant side when the hand was positioned at top-dead center of the handrim (Equation 6 in Appendix F & Figure 14). The elbow angle measurement was used to determine if the wheelchair seat was positioned optimally or non-optimally in the vertical direction according to adult clinical guidelines. If the angle between the upper arm and forearm on the dominant side was found to be between 100-120 degrees, the vertical axle position was defined as optimal. If the elbow angle fell outside of this range, the vertical axle position was defined as non-optimal.

Figure 14: The reflective markers on the acromion process, olecranon process, and ulnar styloid were used to find the sagittal elbow flexion angle, or angle between the forearm and upper arm.

Ultrasound Imaging

Supraspinatus Tendon Thickness. Following ultrasound, captured images of the supraspinatus tendon were analyzed using Horos imaging software (Horos Project, Brooklyn, NY). To quantify tears, degeneration, and inflammation in the supraspinatus tendon, the cross-sectional thickness, longitudinal thickness, cross-sectional area (CSA), and acromiohumeral distance were measured on each participant's dominant side (Figure 15) and the average measurements were reported following image segmentation. Although tendon thickness and CSA can inform clinicians about changes in an individual's supraspinatus over time, these measures are not easily compared across age groups because younger and older children are likely to have drastically different sized tendons. To accommodate for this and to normalize the data so that it could be more easily compared across age groups, the supraspinatus tendon occupation ratio was also found for each subject. The occupation ratio is the percentage of the subacromial space that is occupied by the supraspinatus tendon; this measurement can be more easily compared between participants because it reflects the percentage of space the supraspinatus takes up relative to the child's body size. In previous studies, the occupation ratio has been used to identify predictors of shoulder pathology, such as tendon atrophy and muscle overuse, in a variety of populations, including adult MWUs with SCI (Thomazeau, 1996; Morag, 2006; Belley et al., 2017; Navarro-Ledesma et al., 2021). The occupation ratio was calculated by dividing the supraspinatus tendon thickness by the acromiohumeral distance and multiplying by 100 (Navarro-Ledesma et al., 2021). Protocols used for measuring supraspinatus tendon thickness and CSA are included in Appendix E.



A)

B)

C)

Figure 15: Ultrasound images of the supraspinatus tendon and the humeral head were analyzed in Horos software to find A) the tendon thickness in the cross-sectional view, B) the tendon thickness in the longitudinal view, and C) the tendon cross-sectional area

Pain and Independence Outcomes. WUSPI and SCIM scores were determined based on each of the standardized assessments' scoring criteria. Due to the varying activity levels among subjects, WUSPI performance corrected (PC) scores were calculated and reported rather than raw scores. PC scores are more valuable for data comparison as they reflect the most accurate shoulder pain intensity scores by accounting for different activity levels among subjects (Curtis, Tyner, et al., 1999). The PC scores were calculated by dividing the total raw score by the number of activities the subject performed and multiplying by 15 (Curtis, Tyner, et al., 1999). Only the raw scores were reported for the SCIM-III because this assessment takes into account all item responses in order to calculate independence, so no performance corrected option exists for this outcome measure.

Statistical Analyses

The relationship between wheelchair parameters (seat angle, horizontal axle position, and vertical axle position) and subject demographics (age, time since injury, and SCI lesion level) were examined using Pearson's correlation coefficients and a Spearman-Rho Test. The relationship between wheelchair parameters (seat angle, horizontal axle position, and vertical axle position) and supraspinatus tendon measurements (thickness, CSA, occupation ratio) were also examined using Pearson's correlation coefficients and a Spearman-Rho Test. Finally, the relationship between wheelchair parameters (seat angle, horizontal axle position, and vertical axle position) and subject outcomes (WUSPI pain scores and SCIM-III independence scores) were examined using Pearson's correlation coefficients and a Spearman-Rho Test. A total of 24 correlations were investigated to determine if a relationship exists between wheelchair settings (seat angle, horizontal axle position, and elbow angle) and subject demographics (age and time since injury), supraspinatus tendon measurements (thickness, CSA, occupation ratio), or subject outcomes (WUSPI pain scores and SCIM-III independence scores).

A bivariate-Pearson's correlation and a Spearman's rank order correlation were both run to analyze relationships for all metrics mentioned above, however, relationships were reported based on the Spearman's rank order correlation as this is the more conservative, non-parametric test of the two, and therefore, the more appropriate measure to report due to this study's small sample size. Pearson's correlation and Spearman's correlation coefficients were categorized as either strong ($r = 0.5\text{-}1$), moderate ($r = 0.3\text{-}0.5$), or weak ($r = 0.0\text{-}0.3$). Data was determined to be statistically significant if $p < 0.05$.

Results

Subject Demographics

A total of 9 pediatric manual wheelchair users (4 females, 5 males; 15.1 +/- 6.1 years old; 10.5 +/- 5.6 years since injury) with SCI ranging from the first thoracic vertebra to the third lumbar vertebra (T1-L3) participated in this study. The participants were further split into groups based on their level of injury. These groups were defined as upper thoracic (T1-T6), lower thoracic (T7-T12), and lumbar. There were 5 subjects with upper thoracic SCI, 2 with lower thoracic, and 2 with lumbar injuries. Of the 9 participants, 5 reported having received some level of wheelchair training in the past, but 4 of these reported that the training was minimal and/or only for their initial wheelchair. Of the 9 participants, 8 were right hand dominant, and only 1 was left hand dominant. Average subject measurements were 49.2 kg (+/- 19.5 kg) and 149.0 cm (+/- 25.3 cm). All subject information and demographics are listed in Table 1.

Table 1: Subject demographics

Subject	Gender	Age (years)	Age of Onset (years)	Time Since Injury (years)	Level of Injury	ASIA Score	Height (cm)	Weight (kg)	Dominant Side	Previous Device Training
1	F	13.9	3.7	10.2	T10	A	135	50.2	R	none
2	M	7.5	0.4	7.1	T6	A	110	23.1	R	none
3	F	6.3	2.7	3.6	T6	A	109	15.9	R	3 months
4	M	10.8	5.6	5.3	T4 C	A	152.4	37.2	L	initial chair only
5	F	21.0	16.0	4.9	T5/T6	A	157.5	63.5	R	initial chair only
6	M	21.5	2.7	18.7	L3	D	167.6	66.6	R	none
7	F	21.3	4.4	16.9	T1	A	162.6	63.5	R	none
8	M	13.9	0.4	13.5	L3	D	174	68.5	R	initial chair only
9	M	20.1	6.2	13.9	T7	A	172.7	54.4	R	minimal training
Average		15.1	4.7	10.5			149	49.2		

Aim 1: Pediatric Wheelchair Settings

Seat Angle. It was hypothesized that pediatric MWC users would use sagittal seat angles (dump angles) that were parallel to the ground as opposed to more acute seat angles. All 9 participants had their wheelchairs positioned at sagittal seat angles that were greater than zero degrees but less than 10 degrees of elevation. The average seat angle was 5.16 degrees (+/- 1.66 degrees) of elevation. The straightest seat angle recorded was 2.58 degrees of elevation and the most elevated seat angle recorded was 7.20 degrees of elevation. No participants utilized a straight seat angle that was parallel to the floor. Sagittal seat angles and additional wheelchair measurements for all subjects are listed in Table 2.

Table 2: Subject manual wheelchair measurements.

Subject	Wheel Diameter (in)	Seat Height (mm)	Backrest Height (mm)	Wheelchair Width (mm)	Shoulder Width (mm)	Ratio of Shoulder Width to Wheelchair Width	Seat to Backrest Angle (degrees)	Seat Sagittal (Dump) Angle (degrees)
1	24	510.60	442.92	615.39	304.68	0.50	N/A	2.58
2	22	466.13	325.51	531.08	220.83	0.42	99.41	7.20
3	22	436.58	311.71	497.22	208.03	0.42	92.86	5.26
4	22	460.48	389.51	612.60	237.51	0.39	95.73	3.95
5	24	480.09	277.71	588.26	339.32	0.58	104.36	3.56
6	24	468.34	301.55	656.47	361.13	0.55	95.28	6.32
7	24	572.44	259.89	630.78	302.13	0.48	101.94	6.18
8	24	508.43	373.00	573.18	332.28	0.58	89.85	4.27
9	24	548.69	291.57	614.74	275.44	0.45	85.05	7.15
Average		494.64	330.38	591.08	286.82	0.48	95.56	5.16

Horizontal Axle Position. It was hypothesized that pediatric MWC users would have their axles horizontally positioned more rearward in relation to their shoulders during wheelchair propulsion. Of the 9 subjects who participated in the study, 78% (7 subjects) had their axles positioned aft of the acromion process during wheelchair propulsion. Only 2 participants had axle positions that were, on average, more forward than the shoulder during wheelchair propulsion, and only 1 of these participants maintained a more forward axle position throughout all recorded stroke cycles. The average fore-aft position of the shoulder relative to the wheel axle was fore 69.73 mm (+/- 68.50 mm). The subject with the most rearward axle position relative to the shoulder had an average ACR x position that was 161.8mm fore of the axle. The subject with the most forward axle position relative to the shoulder had an average ACR x position of -35.49mm, or 35.49mm aft of the axle. The average maximum fore-aft position of the shoulder relative to the wheel axle for all participants was fore 84.96 mm (+/- 84.55 mm). The maximum average ACR x positioned recorded over all cycles was 181.24mm fore of the axle, and the minimum average ACR x position recorded was -47.37mm, or 47.47mm aft of the axle. Overall, most participants spent a majority of their push time with their axles positioned behind their shoulders or with a more rearward horizontal axle position. Average subject shoulder positions relative to the wheel axle are listed in Table 3.

Table 3: The average ACR x position with respect to the axle for each subject for all cycles.

Subject	Average Max ACR X Position wrt to Axle for All Cycles (mm)	Average ACR X Position wrt to Axle for All Cycles (mm)	AXL Position wrt ACR
1	131.51	107.81	Aft, rearward axle
2	180.46	161.80	Aft, rearward axle
3	-44.51	-17.51	Fore, forward axle
4	81.40	63.55	Aft, rearward axle
5	116.39	77.88	Aft, rearward axle
6	-47.37	-35.49	Fore, forward axle
7	56.77	37.18	Aft, rearward axle
8	181.24	157.68	Aft, rearward axle
9	108.71	74.67	Aft, rearward axle
Average	84.96	69.73	

Vertical Axle Position. It was hypothesized that most pediatric MWC users would have axles that were positioned non-optimally in the vertical axis based on the adult recommendation of an elbow angle between 100-120 degrees when the hands are at top dead center of the pushrim. In terms of vertical seat and axle position, 4 subjects (44%) had their seats optimally positioned based on adult clinical guidelines, so that their elbow flexion angles were within 100-120 degrees when at top dead center of the handrims. The other 5 subjects (56%) had their seats non-optimally positioned, defined by elbow angles outside of the recommended 100-120 degrees. The average elbow angle on the dominant side with the hand positioned at top dead center was 99.79 degrees (+/- 13.65 degrees). The smallest elbow angle recorded was 79.54 degrees while the largest elbow angle recorded was 126.51 degrees. Overall, a majority of participants used non-optimal elbow flexion angles according to adult guidelines, and therefore, non-optimal vertical axle positions. All subjects' elbow angle measurements are listed in Table 4.

Table 4: Subject elbow flexion angles in static, seated position with dominant hand at top dead center of the pushrim.

Subject	Elbow Flexion Angle on Dominant Side at Top Dead Center (degrees) using ACR, OLC, ULN markers	Group based on Adult Recommendations (optimal: 100-120; non-optimal <100, >120 degrees)
1	106.00	optimal
2	103.45	optimal
3	79.54	non-optimal
4	100.06	optimal
5	106.24	optimal
6	84.23	non-optimal
7	95.03	non-optimal
8	126.51	non-optimal
9	97.04	non-optimal
Average	99.79	

Aim 2: Effects of SCI Level, Age, and Time Since Injury

Seat Angle It was hypothesized that pediatric MWC users with SCI would use different seat angles based on their level of injury, age, and time since injury.

Level of Injury. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 9 participants' level of injury and seat angle. No correlation between SCI lesion level and seat angle were found (r=-.111, p=0.777; r_s=0.076, p=0.847) as the seat angles used did not vary much between groups (see Figure 16). The average, minimum, and maximum seat angles for each lesion level group are listed in Table 5. The seat angles being used varied greatly across injury levels; however, the lower thoracic group demonstrated the most variation with one participant using close to the largest seat angle (7.15 degrees) and the other participant using the smallest seat angle (2.58 degrees).

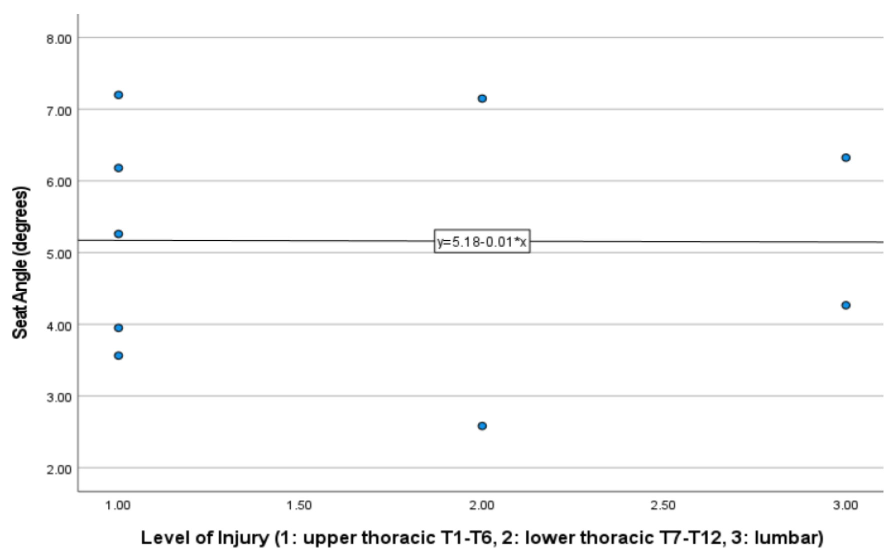


Figure 16: Scatter plot depicting that there is no relationship between the SCI lesion level and the wheelchair seat angle.

Table 5: Descriptive statistics for seat angle based on SCI lesion level group.

	Seat Angle (Degrees)			
SCI Lesion Level Group	Mean	Std. Error	Minimum	Maximum
Upper Thoracic (T1-T6)	5.23	0.68	3.56	7.2
Lower Thoracic (T7-T12)	4.87	2.28	2.58	7.15
Lumbar	5.30	1.03	4.27	6.32

Age. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 9 participants' age and seat angle. A weak positive correlation was found between age and seat angle that was insignificant (r=.089, p=0.821; r_s =0.017, p=0.966) (Figure 17)***.*** As participants got older, they were slightly more likely to use a larger seat angle. The seat angles beings used by the MWC users varied across age groups, however, 3 of the 4 largest seat angles recorded were used by the oldest participants (20 years of age or older). The average age of those who used a seat angle less than 5 degrees (N=4) was 14.91 +/- 4.3 years. The average age of those who used a seat angle more than 5 degrees (N=5) was 15.32 +/- 7.74 years.

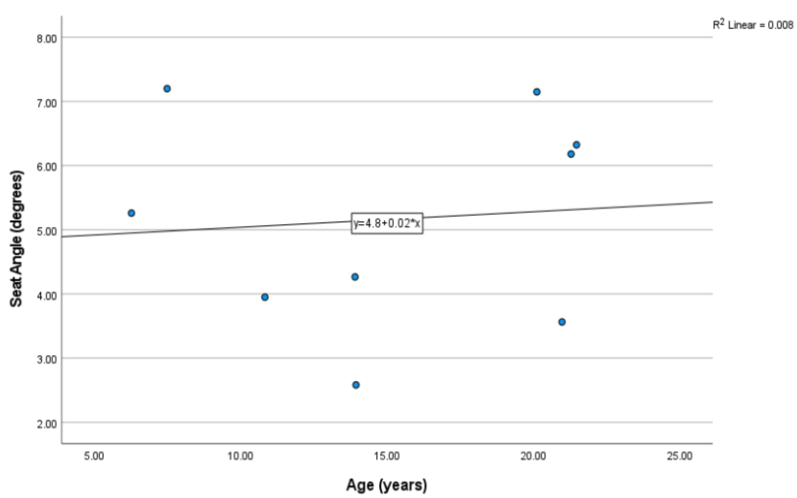


Figure 17: Scatter plot depicting the weak positive correlation between participant age and the wheelchair seat angle.

Time Since Injury. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 9 participants' time since injury and seat angle. A moderate positive correlation was found between time since injury and seat angle that was insignificant (r=0.386, p=0.305; rs =0.417, p=0.265) (Figure 18). The participants with a longer time since injury tended to have larger seat angles when compared to the rest of the group. Similar to the previous metric, 3 of the 4 participants with the largest recorded seat angles have also had their SCIs for the longest amount of time (12 years or more). The average time since injury for those who used a seat angle less than 5 degrees (N=4) was 8.48 +/- 4.13 years. The average time since injury for those who used a seat angle more than 5 degrees (N=5) was 12.04 +/- 6.48 years.

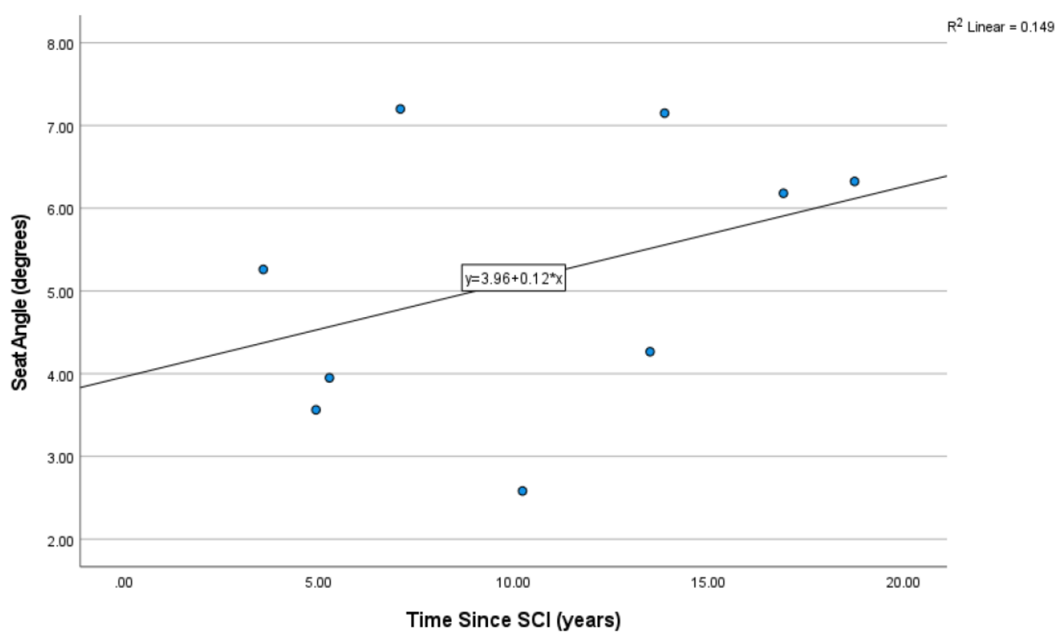


Figure 18: Scatter plot depicting the moderate positive correlation between participant time since injury and the wheelchair seat angle.

Horizontal Axle Position It was hypothesized that pediatric MWC users with SCI would use different horizontal axle positions based on their level of injury, age, and time since injury.

Level of Injury. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 9 participants' level of injury and the horizontal axle position of their wheelchair. There was a weak correlation between horizontal shoulder positions (ACR x position) with respect to the axle based on injury levels that was insignificant ($r=0.018$, $p=0.964$; $r_s=0.028$, $p=0.944$) (Figure 19). The average, minimum, and maximum ACR X positions for each lesion level group are listed in Table 6. The participants with lower SCI lesion levels tended to have more positive ACR X positions, and therefore, more rearward axle positions. The horizontal shoulder position relative to the axle varied greatly across injury levels, however, the lower thoracic group showed the most consistency as it was the only group where all participants used rearward axle positions during wheelchair propulsion. In contrast, the 2 participants with the most forward axle positions and the 2 participants with the most rearward axle positions were evenly split between the upper thoracic and the lumbar groups.

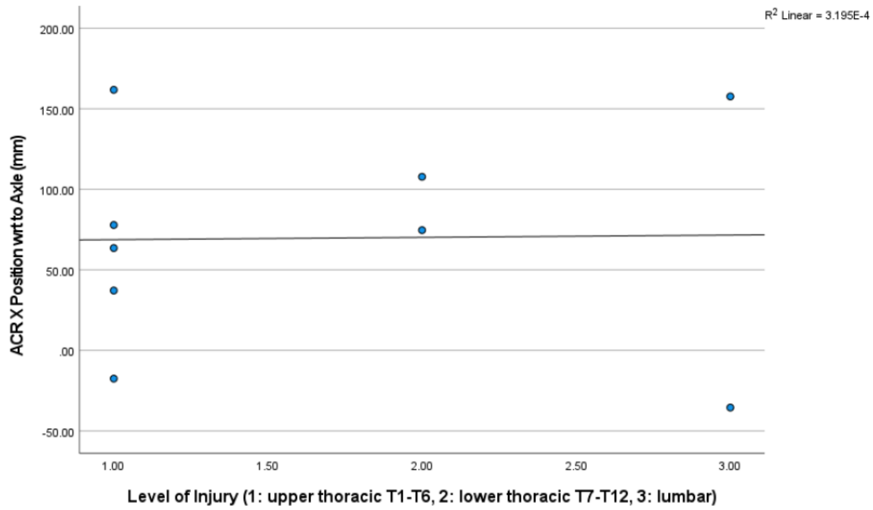


Figure 19: Scatter plot depicting the weak correlation between a lower SCI lesion level and a more positive horizontal axle position.

Table 6: Descriptive statistics for horizontal axle position based on SCI lesion level group.

	ACR X Position wrt AXL (mm)			
SCI Lesion Level Group	Mean	Std. Error	Minimum	Maximum
Upper Thoracic (T1-T6)	64.58	29.26	-17.51	161.8
Lower Thoracic (T7-T12)	91.24	16.57	74.67	107.81
Lumbar	61.09	96.59	-35.49	157.68

Age. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 9 participants' age and the horizontal axle position of their wheelchair. A moderate negative correlation was found between age and ACR x position with respect to the axle that was insignificant ($r=-0.256$, $p=0.506$; $rs=-0.35$, $p=0.356$) (Figure 20)**.** The average age of those who used a forward axle position (N=2) was 13.87 +/-

10.74 years. The average age of those who used a rearward axle position (N=7) was 15.5 +/- 5.41 years. As participants increased in age, they tended to have less rearward axle positions. For example, the 2 oldest participants in the study had ACR x positions that were below the group average (69.73 mm), and therefore, had less rearward horizontal axle positions when compared to the other subjects**.** Interestingly, the youngest and the oldest of the participants were the only ones to maintain forward axle positions relative to the shoulder during wheelchair propulsion.

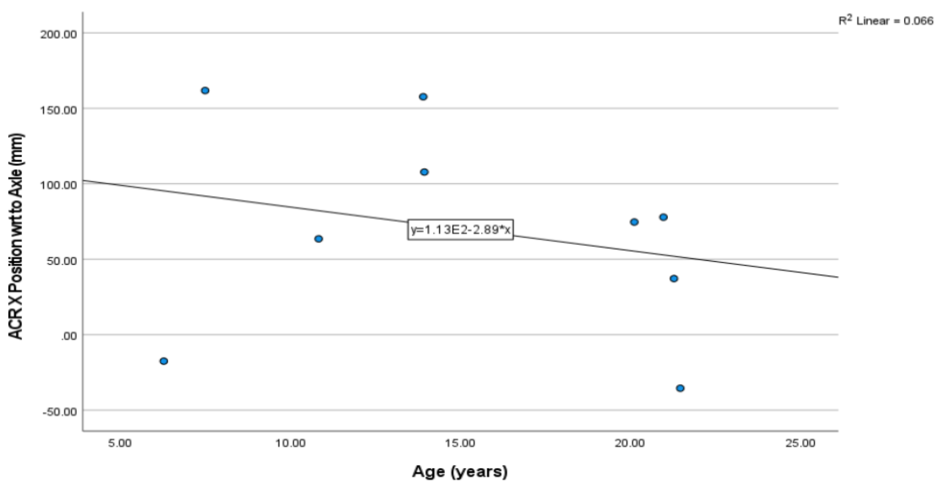


Figure 20: Scatter plot depicting the moderate negative correlation between age and the horizontal axle position.

Time Since Injury. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 9 participants' time since injury and the horizontal axle position of their wheelchair. A weak negative correlation was found between time since injury and the ACR x position with respect to the axle that was insignificant (r=-0.174, p=0.655; rs = -0.2, p=0.606) (Figure 21). The average time since injury for those who used a forward axle position (N=2) was 11/16 +/-10.72 years. The average time since injury for those who used a rearward axle position (N=7) was 10.26 +/- 4.67 years. Again, the subject with the shortest amount of time since injury and the subject with the longest amount of time since injury were the only participants to maintain forward axle positions throughout wheelchair propulsion. Of the 4 participants who had ACR x positions that were below the average for the group (more forward horizontal axle positions when compared to peers), 2 of them were among the participants with the least amount of time since injury (less than 6 years old) and 2 of them were among the participants with the longest amount of time since injury (more than 15 years). Participants in the middle range of time since injury (6-15 years) demonstrated the largest ACR x positions, and therefore, the most rearward horizontal axle positions.

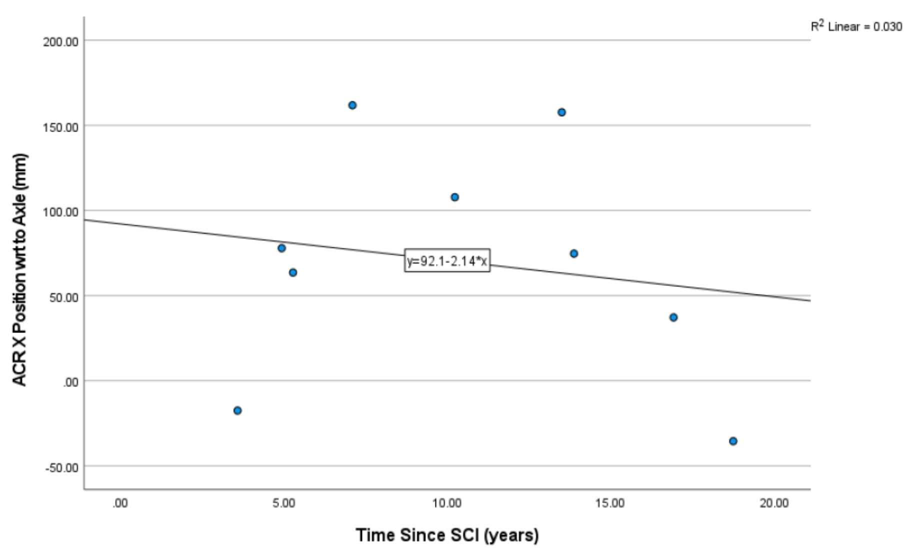


Figure 21: Scatter plot depicting the weak negative correlation between time since injury and the horizontal axle position.

Vertical Axle Position It was hypothesized that pediatric MWC users with SCI would use different vertical axle positions based on their level of injury, age, and time since injury.

Level of Injury. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 9 participants' level of injury and the vertical axle position of their wheelchair. A weak correlation was found between a lower level of injury and an increased elbow angle at top dead center that was insignificant (r=0.266, p=0.489, rs =0.168, p=0.666) (Figure 22). The average, minimum, and maximum elbow flexion angles for each lesion level group are listed in Table 7. The vertical axle position, as measured by the elbow angle at top dead center, varied greatly across injury levels, however, the participants with the lowest injury levels (lumbar lesions at L3) demonstrated the largest amount of variation, with all participants in this group falling outside of the optimal elbow angle range.

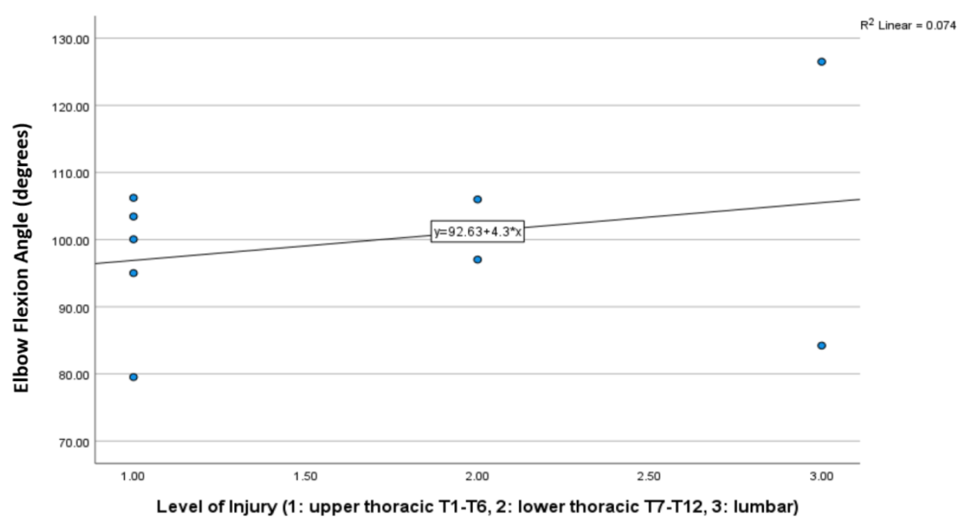


Figure 22: Scatter plot depicting the weak positive correlation between a lower SCI lesion level and a larger elbow flexion angle.

Table 7: Descriptive statistics for elbow flexion angle based on SCI lesion level group.

SCI Lesion Level Group	Elbow Flexion Angle (degrees)			
	Mean	Std. Error	Minimum	Maximum
Upper Thoracic (T1-T6)	96.86	4.72	79.54	106.24
Lower Thoracic (T7-T12)	101.52	4.48	97.04	106
Lumbar	105.37	21.12	84.23	126.51

Age. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 9 participants' age and the vertical axle position of their wheelchair. No correlation was found between age and the elbow angle at top dead center (r=0.009, p=0.981; rs = -0.067, p=0.865), but a weak positive correlation was found between increasing age and the use of a non-optimal elbow angle that was insignificant (r=0.286, p=0.455; rs =0.26, p=0.5) (Figure 23). The older participants tended to have elbow angles that fell outside of the recommended 100-120 degrees. For example, of the 4 oldest participants (> 20 years), 75% of them utilized a non-optimal vertical axle position as demonstrated by their elbow angles. Interestingly, however, the youngest participant also utilized a non-optimal elbow angle. The average age of the participants who used optimal vertical axle positioning (N=4) was 13.3 years +/- 2.87 years while the average age of the participants who used non-optimal vertical axle positioning (N=5) was 16.6 years +/-2.93 years (Figure 24).

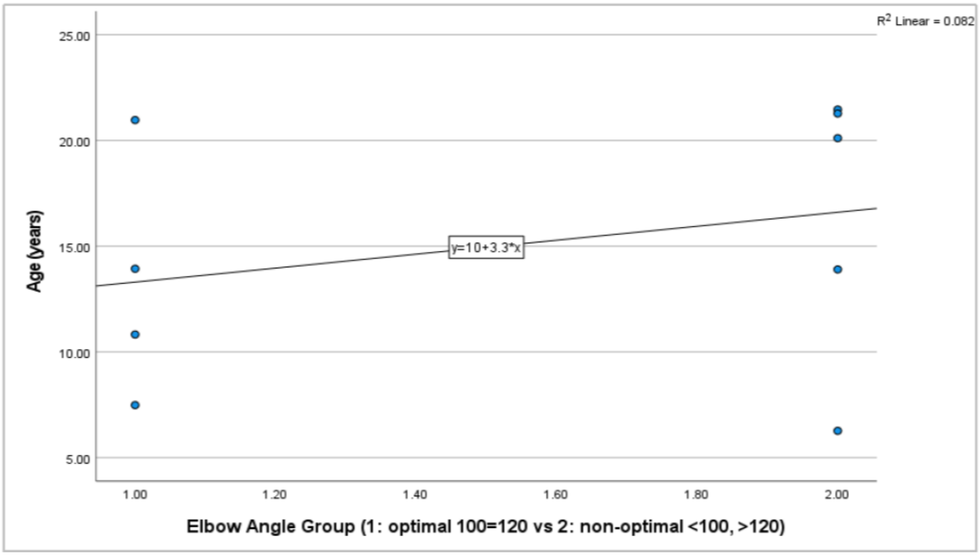


Figure 23: Scatter plot depicting the weak correlation between increasing age and the use of a non-optimal elbow angle.

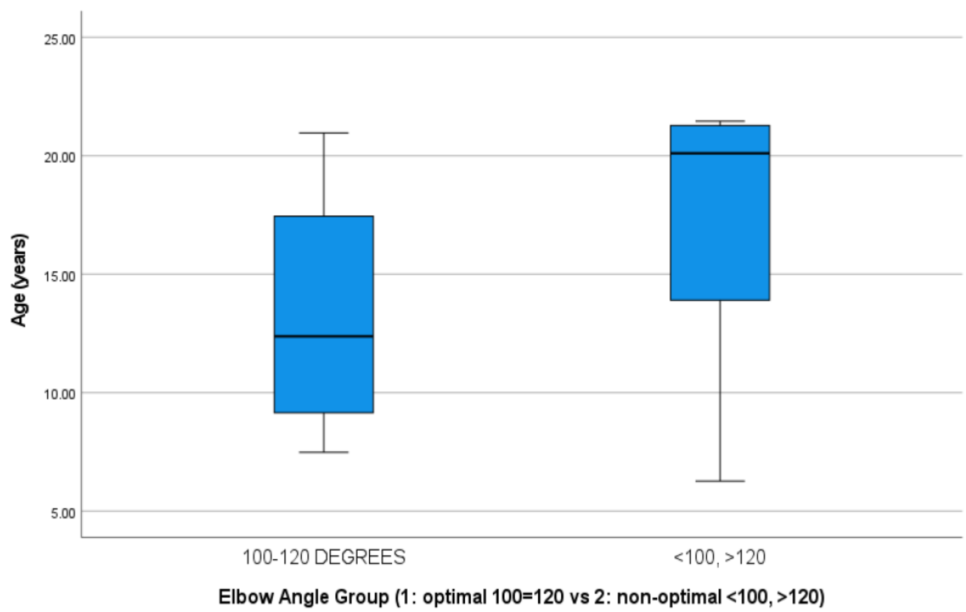


Figure 24: Histogram comparing the age statistics for the group of participants who used an optimal elbow angle to the group of participants who used a non-optimal elbow angle.

Time Since Injury. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 9 participants' time since injury and the vertical axle position of their wheelchair No correlation was found between time since injury and the elbow angle at top dead center ($r=0.001$, $p=0.998$; $r_s =-0.167$, $p=0.668$), however, a strong positive correlation was found between time since injury and the use of a non-optimal elbow angle that was insignificant ($r=0.61$, $p=0.81$; $r_s =0.52$, $p=0.152$) (Figure 25)***.*** Participants who had their SCIs for longer periods of time were more likely to use a non-optimal elbow angle. Of the 5 participants who demonstrated non-optimal elbow angles, 4 of those were subjects for whom it had been more than 10.5 years since their SCI (average time since injury for the group). On the other hand, all 4 of the participants who used an optimal vertical axle position had their SCI for fewer than 10.5 years. Interestingly, the participant with the least amount of time since their injury also utilized a non-optimal elbow angle. The average time since injury for the participants who used optimal vertical axle positioning (N=4) was 6.88 years +/- 1.21 years while the average time since injury for the participants who used non-optimal vertical axle positioning (N=5) was 13.32 years +/-2.62 years (Figure 26).

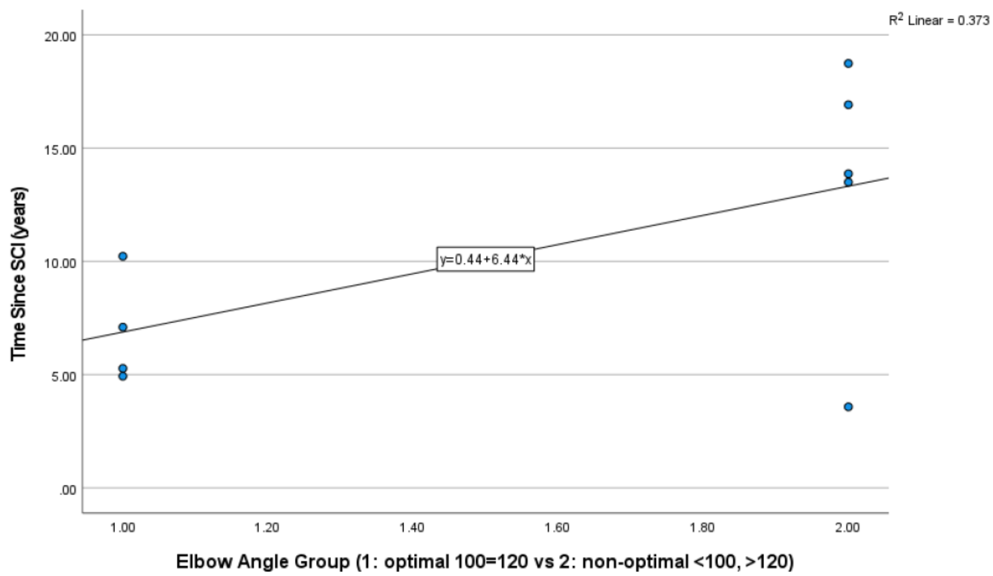


Figure 25: Scatter plot depicting the strong positive correlation between time since injury and the use of a non-optimal elbow angle.

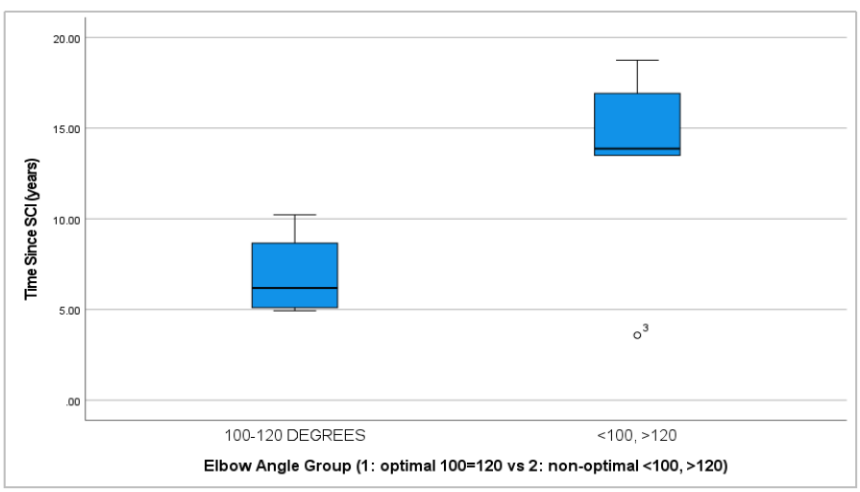


Figure 26: Histogram comparing the time since injury statistics of participants based upon their use of either an optimal or a non-optimal elbow angle.

Aim 3: Pathology & Supraspinatus Tendon Thickness

Only 1 subject had positive special test results during the clinical exam, but visible shoulder pathologies were identified using ultrasound in 4 of the 9 participants (44%). Pathologies identified included AC joint osteophytes, subacromial bursitits, AC joint effusion, and supraspinatus tendonitis. Supraspinatus tendon thicknesses also varied among each of the subjects. The average supraspinatus tendon thickness for all subjects in the longitudinal view was 0.56 (+/- 0.15) cm with a range from 0.41-0.92 cm. The average supraspinatus tendon thickness in the cross-sectional view was 0.62 (+/- 0.18) cm with a range from 0.43-0.91 cm. The average supraspinatus tendon thickness for all directional views was 0.59 (+/-0.15) cm with a range from 0.44-0.92 cm. The average cross-sectional area of the supraspinatus tendon for all subjects was 10.38 (+/-4.95) cm^2 with a range from 4.53-18.78 cm^2. Finally, the average occupation ratio for all participants was 69.62 (+/-10.99) % with a range from 55.77-86.74%. Ultrasound findings for all subjects and descriptive statistics for supraspinatus tendon measurements are listed in Table 8.

Previous studies report that the average supraspinatus tendon thickness for young healthy adults is 0.44-0.51 cm for men and 0.38-0.46 mm for women (Karthikeyan et al., 2014; Kim et al., 2016). In this study, the average supraspinatus tendon thickness was slightly larger than what has been reported in healthy adults. Similarly, Kim et al. (2011) found that the average occupation ratio for the supraspinatus muscles in healthy adults was 85% (Kim et al., 2011). According to Thomazeau's classification, an occupation ratio between 60-100% represents normal or mild atrophy, a range between 40-60% represents moderate atrophy, and an occupation ratio below 40% indicates severe atrophy (Thomazeau et al., 1996). In the current study, 2 participants had occupation ratios within the moderate atrophy range, and the average occupation ratio was slightly lower than what has been reported in adults.

Table 8: Subject pathology data including supraspinatus tendon thickness, cross-sectional areas, and occupation ratios.

Subject	Pathology Present	Supraspinatus Tendon Thickness - Cross Sectional (cm)	Supraspinatus Tendon Thickness - Longitudinal (cm)	Supraspinatus Tendon Thickness - Both (cm)	Supraspinatus Tendon Thickness - CSA (cm^2)	Occupation Ratio (%)
1	no pathology	0.84	0.60	0.70	18.78	80.92
2	no pathology	0.76	0.56	0.66	7.54	55.77
3	no pathology	0.63	0.59	0.61	4.53	86.74
4	AC joint osteophytes; subacromial bursitis	0.91	0.92	0.92	5.68	68.69
5	no pathology	0.47	0.45	0.46	15.42	79.26
6	tenosynovitis of bicep	0.57	0.41	0.49	14.63	62.88
7	AC joint osteophytes; subacromial bursitis	0.44	0.51	0.48	11.50	72.16
8	tendonitis of supraspinatus tendon; AC joint osteophytes; AC joint effusion' subacromial bursitis	0.55	0.56	0.56	8.61	56.51
9	no pathology	0.43	0.45	0.44	6.76	63.68
Mean		0.62	0.56	0.59	10.38	69.62
Standard Deviation		0.17	0.15	0.15	4.95	10.99
Minimum		0.43	0.41	0.44	4.53	55.77
Maximum		0.91	0.92	0.92	18.78	86.74

Seat Angle. It was hypothesized that pediatric MWC users with SCI who used straighter seat angles would have larger supraspinatus tendons than those who used more acute seat angles. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 9 participants' seat angle and the thickness of their supraspinatus tendon. A moderate negative correlation was found between seat angle and supraspinatus tendon thicknesses that were insignificant ($r=-0.414$, $p=0.268$; $r_s=-0.317$, $p=0.406$) (Figure 27); a moderate negative correlation was found between seat angle and supraspinatus tendon CSA that were insignificant $r=-0.456$., $p=0.217$; $r_s=-0.4$, $p=0.286$) (Figure 28); and a strong negative correlation was found between seat angle and supraspinatus tendon occupation ratios that were insignificant ($r=-0.517$, $p=0.154$; $r_s=-0.617$, $p=0.077$) (Figure 29). Participants who used wheelchairs with larger seat angles or more elevated seats tended to have smaller supraspinatus tendons while those who used straighter seat angles or flatter wheelchair seats tended to have larger supraspinatus tendons. For example, the 2 participants with the smallest, or straightest, seat angles were also the two participants with the largest supraspinatus cross-sectional areas. Similarly, 3 of the 4 participants with the smallest occupation ratios also utilized the largest wheelchair seat angles. The average tendon measurements of those who used a seat angle of less than 5 degrees (N=4) and those who used a seat angle of more than 5 degrees (N=5) are listed in Table 9.

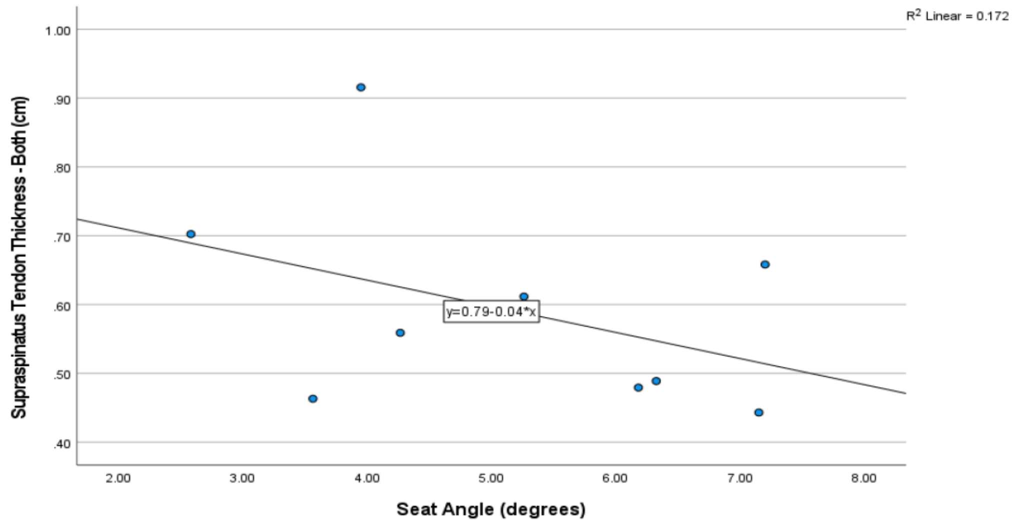


Figure 27: Scatter plot depicting the moderate negative correlation between seat angle and supraspinatus tendon thickness.

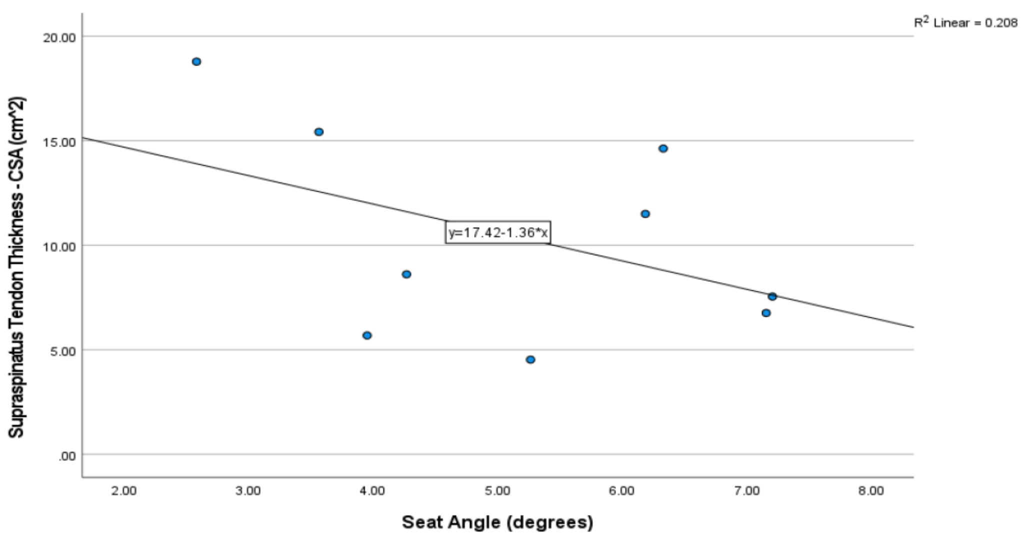


Figure 28: Scatter plot depicting the moderate negative correlation between seat angle and supraspinatus tendon CSA.

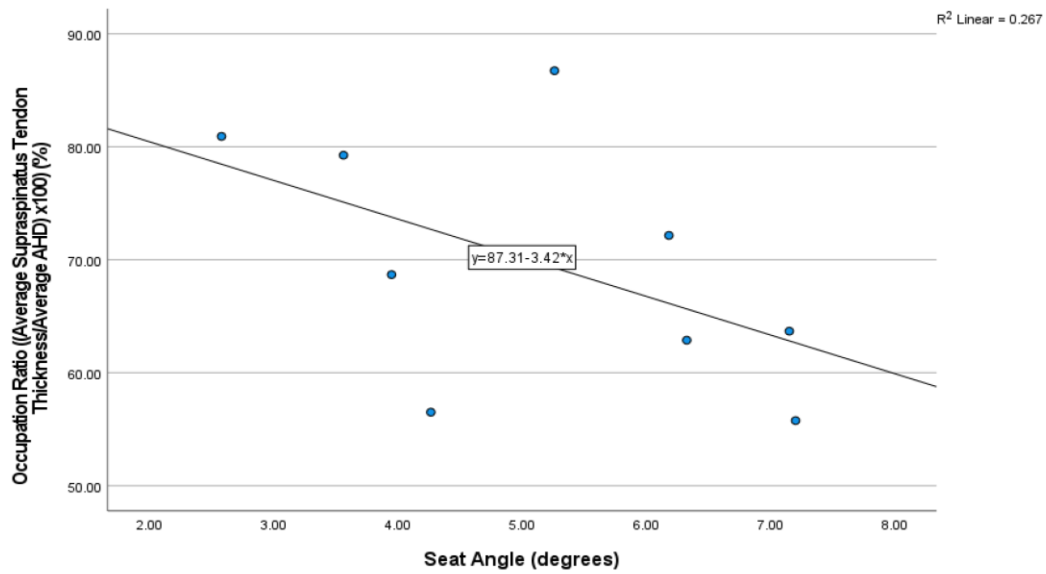


Figure 29: Scatter plot depicting the strong negative correlation between seat angle and supraspinatus occupation ratio.

Table 9: Average supraspinatus tendon measurements for group who used a more acute seat angle (>5 degrees) and for group who use a straighter seat angle (<5 degrees).

	Average Supraspinatus Tendon Thickness - Both (cm)	Standard Deviation (cm)	Average Supraspinatus Tendon Thickness - CSA (cm^2)	Standard Deviation (cm^2)	Average Occupation Ratio (%)	Standard Deviation (%)
< 5 degrees	0.66	0.20	12.12	6.03	71.34	11.28
> 5 degrees	0.54	0.09	8.99	4.03	68.25	11.86

Horizontal Axle Position. It was hypothesized that pediatric MWC users with SCI whose wheelchair axles were positioned more rearward in relation to the shoulder during wheelchair propulsion would have larger supraspinatus tendons than those with more neutral or more forward axle positioning due to inflammation. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 9 participants' horizontal axle positions and the thickness of their supraspinatus tendon. A weak positive correlation was found between ACR x position with respect to the axle and supraspinatus tendon thickness ($r=.197$, $p=0.611$; $r_s=0.2$; $p=0.606$) (Figure 30), while no correlation was found between ACR x position and supraspinatus CSA ($r=-0.006$, $p=0.987$; $r_s=0.2$, $p=0.606$) (Figure 31). A moderate, but insignificant, negative correlation was found between the ACR horizontal position and the occupation ratio of the supraspinatus tendon ($r=-0.467$, $p=0.205$; $r_s=-0.383$, $p=0.308$) (Figure 32). Participants with smaller or more negative ACR x positions tended to have smaller tendon thicknesses but larger occupation ratios, signifying that those with more forward axle positions tended to have thinner supraspinatus tendons but larger occupation ratios. For example, the 2 participants with the most positive ACR x positions, or the most rearward axles, were also the 2 participants with the smallest occupation ratios. The subject with the largest occupation ratio was 1 of the 2 subjects that maintained a forward horizontal axle position throughout all stroke cycles during wheelchair propulsion. The average supraspinatus tendon measurements for the participants who used a forward axle (N=2) and the participants who used a rearward axle (n=7) are listed in Table 10.

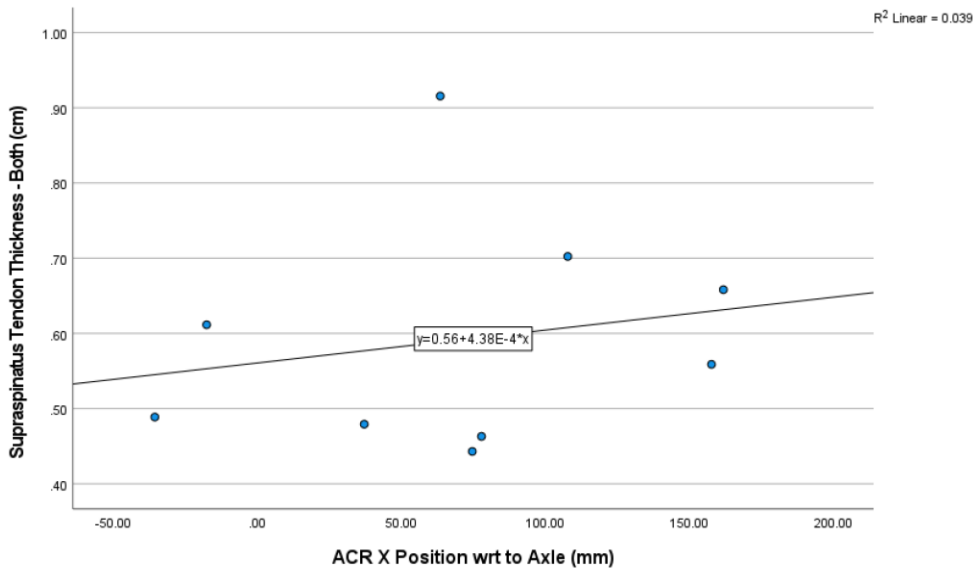


Figure 30: Scatter plot depicting the weak positive correlation between horizontal axle position and supraspinatus tendon thickness.

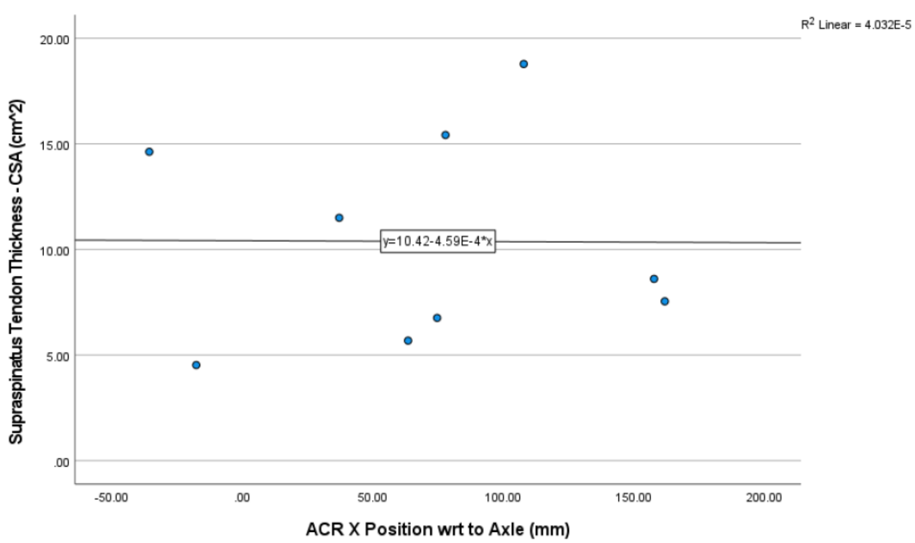


Figure 31: Scatter plot depicting no correlation between horizontal axle position and supraspinatus tendon CSA.

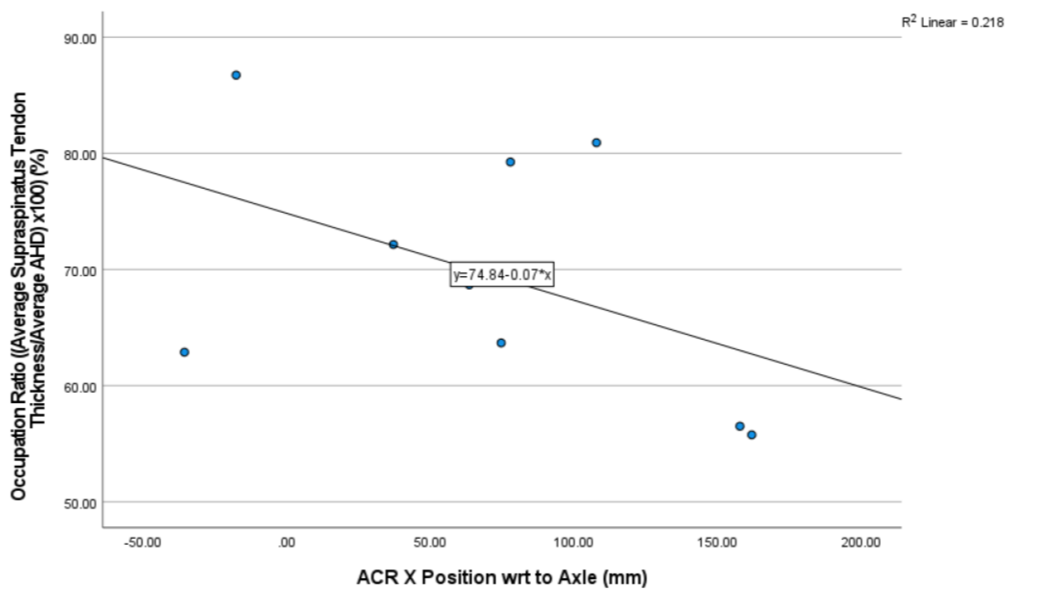


Figure 32: Scatter plot depicting the moderate negative correlation between horizontal axle position and supraspinatus tendon occupation ratio.

Table 10: Average supraspinatus tendon measurements for group who used a rearward axle position and for group who used a forward axle position.

	Average Supraspinatus Tendon Thickness - Both (cm)	Standard Deviation (cm)	Average Supraspinatus Tendon Thickness - CSA (cm^2)	Standard Deviation (cm^2)	Average Occupation Ratio (%)	Standard Deviation (%)
Rearward Axle Position	0.60	0.17	10.61	4.89	68.14	10.10
Forward Axle Position	0.55	0.09	9.58	7.14	74.81	16.87

Vertical Axle Position. It was hypothesized that pediatric MWC users with SCI whose wheelchair axles were positioned non-optimally in the vertical axis (outside of the 100-120 degrees range) would have larger supraspinatus tendons than those with optimal vertical axle positioning**.** A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 9 participants' vertical axle position and the thickness of their supraspinatus tendon. A weak positive correlation was found between elbow angle at top dead center and supraspinatus tendon thickness that was insignificant ($r=0.088$, $p=0.822$; $r_s=0.1$, $p=0.798$) (Figure 33); a moderate positive correlation was found between elbow angle and supraspinatus cross-sectional area that was insignificant ($r=0.153$, $p=0.694$; $r_s=0.433$, $p=0.244$) (Figure 34); and a weak negative correlation was found between elbow angle and occupation ratio ($r=-0.422$, $r=0.257$; $r_s=-0.25$, $p=0.516$) (Figure 35). The participant with the smallest elbow flexion angle had the largest occupation ratio while the participant with the largest elbow angle had close to the lowest occupation ratio.

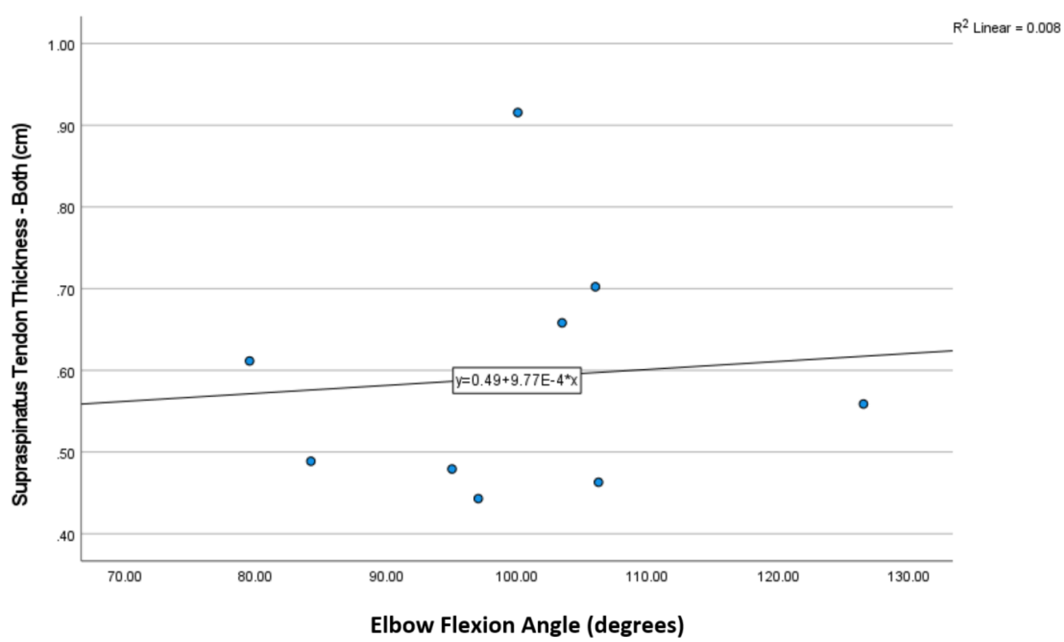


Figure 33: Scatter plot depicting the weak positive correlation between elbow flexion angle and supraspinatus tendon thickness.

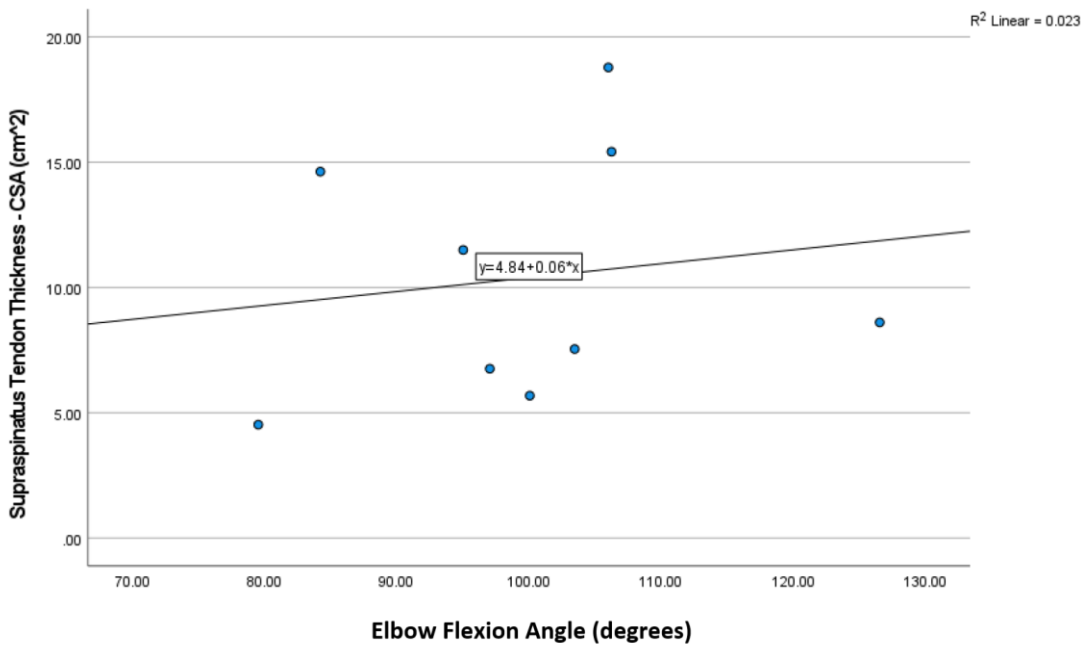


Figure 34: Scatter plot depicting the moderate positive correlation between elbow flexion angle and supraspinatus tendon CSA.

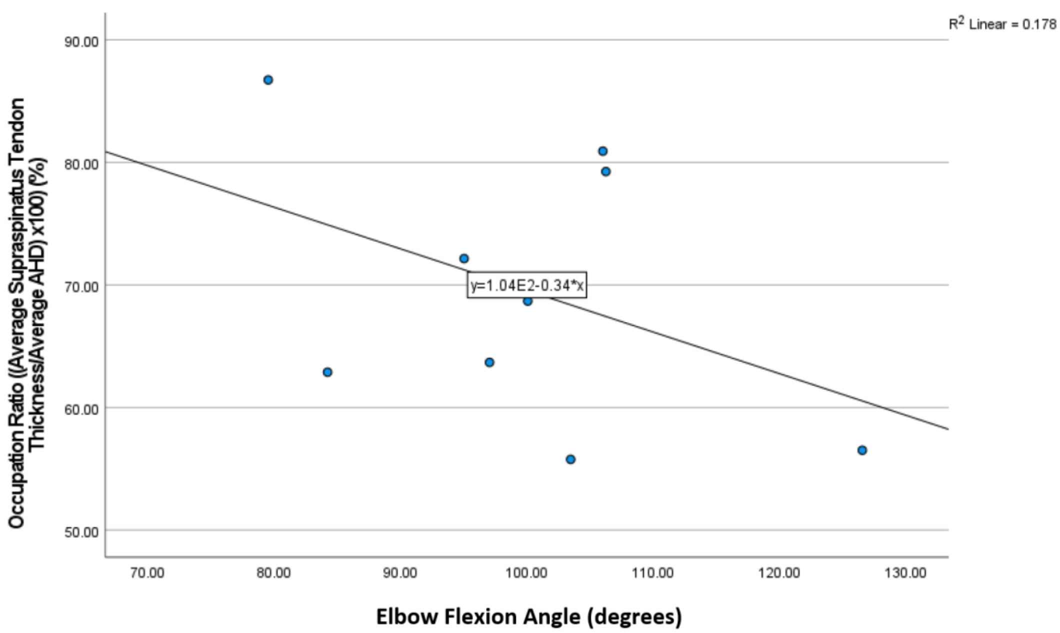


Figure 35: Scatter plot depicting the weak negative correlation between elbow flexion angle and supraspinatus tendon occupation ratio.

When participants were separated into optimal and non-optimal elbow angle groups based on adult recommendation, similar correlations were found. The descriptive statistics for the three supraspinatus tendon measurements based on each group are listed in Table 11. The supraspinatus tendon measurements varied among the group of participants who used optimal vertical axle positioning (N=4) and the group of participants who used non-optimal vertical axle positioning (N=5) (Figures 36-38). Based on this data, a strong, but insignificant, correlation was found between the use of an optimal elbow angle and a larger supraspinatus tendon thickness ($r=-0.584$, $p=0.099$, $r_s=-0.52$, $p=0.152$) (Figure 39). This was further demonstrated when 80% (4/5) of the participants who used a non-optimal elbow angle had supraspinatus tendon thicknesses that were below the mean thickness calculated for the entire group (0.591 cm). Similarly, a weak correlation was found between the use of an optimal elbow angle and a larger supraspinatus CSA that was insignificant ($r=-0.283$, $p=0.461$; $r_s=-0.26$, $p=0.5$) (Figure 40). Finally, a weak correlation was found between the use of an optimal elbow angle and a larger occupation ratio that was insignificant ($r=-0.133$, $p=0.734$; $r_s=-0.087$, $p=0.825$) (Figure 41). Overall, participants who used an optimal elbow angle based on adult recommendations (100-120 degrees) tended to have larger supraspinatus tendons as measured by thickness, CSA, and occupation ratio.

Table 11: Descriptive statistics for supraspinatus tendon dimensions for the group using an optimal elbow angle (100-120 degrees) and the group using a non-optimal elbow angle (<100, >120 degrees).

		Optimal Elbow Flexion Angle (100-120 degrees)	Non-Optimal Elbow Flexion Angle (<100, >120 degrees)
Supraspinatus Tendon Thickness - Both (cm)	Mean	0.68	0.516
	Standard Deviation	0.093	0.03
	Minimum	0.46	0.44
	Maximum	0.92	0.61
Supraspinatus Tendon Thickness - CSA (cm^2)	Mean	11.86	9.20
	Standard Deviation	3.13	1.77
	Minimum	5.68	4.53
	Maximum	18.78	14.63
Occupation Ratio (%)	Mean	71.16	68.39
	Standard Deviation	5.80	5.22
	Minimum	55.77	56.51
	Maximum	80.92	86.74

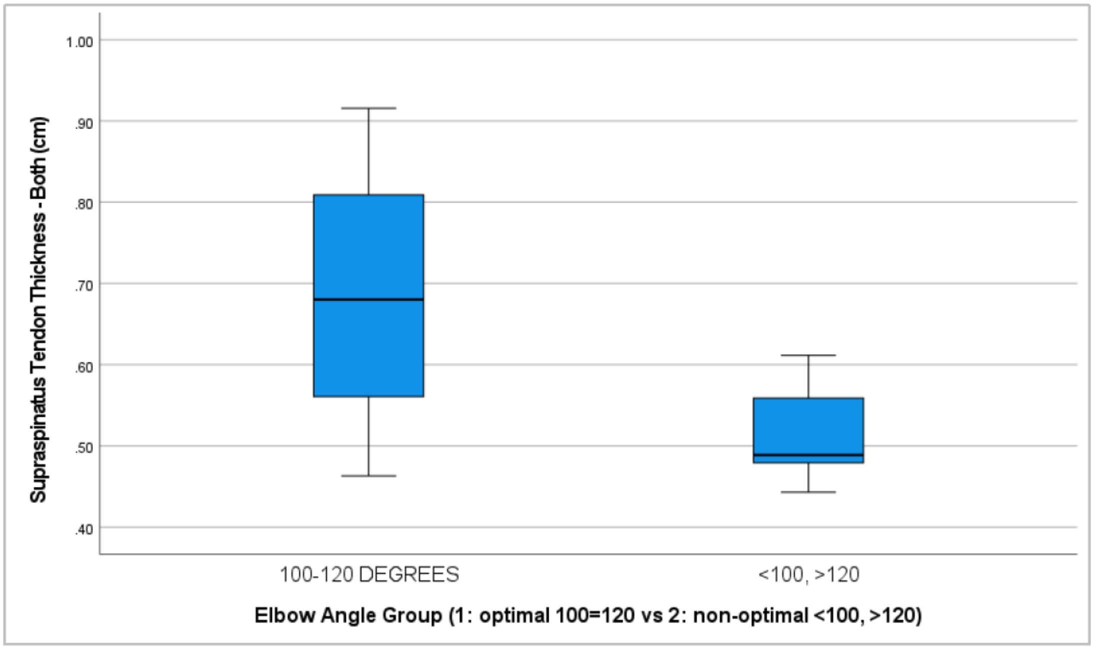


Figure 36: Histogram comparing the supraspinatus tendon thickness statistics of participants based upon their use of either an optimal or a non-optimal elbow angle.

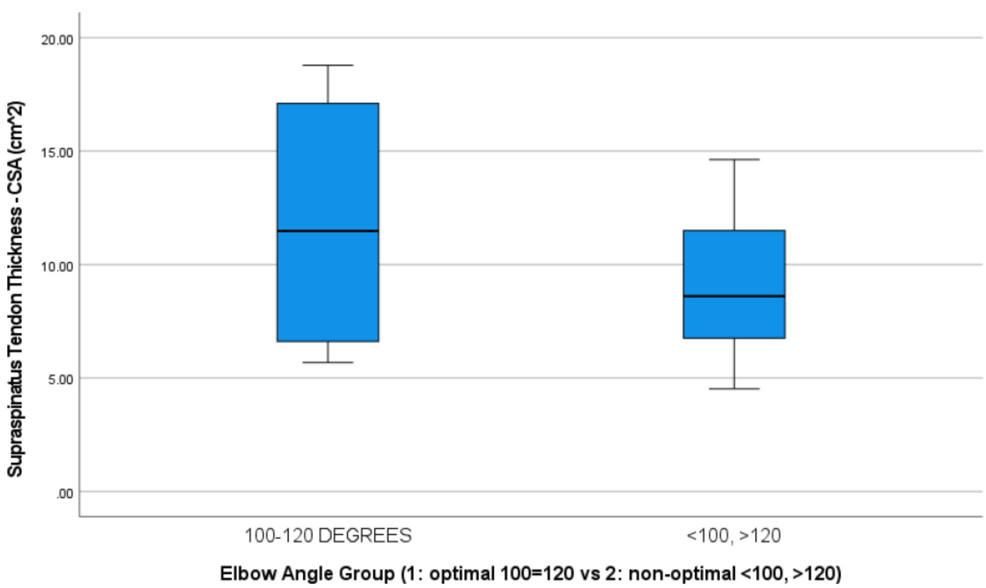


Figure 37: Histogram comparing the supraspinatus tendon CSA statistics of participants based upon their use of either an optimal or a non-optimal elbow angle.

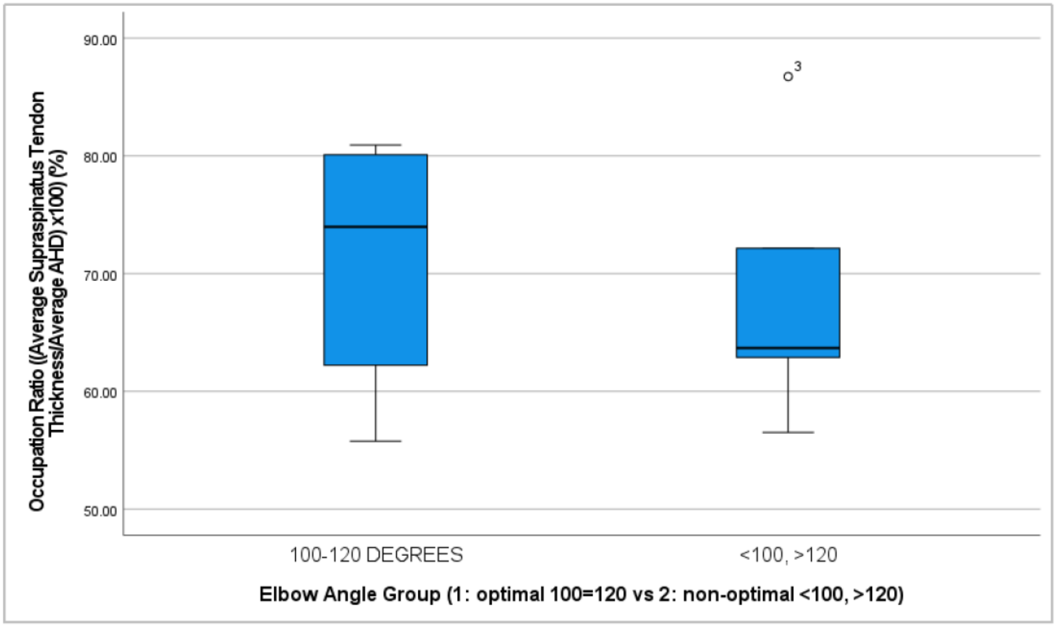


Figure 38: Histogram comparing the supraspinatus tendon occupation ratio statistics of participants based upon their use of either an optimal or a non-optimal elbow angle.

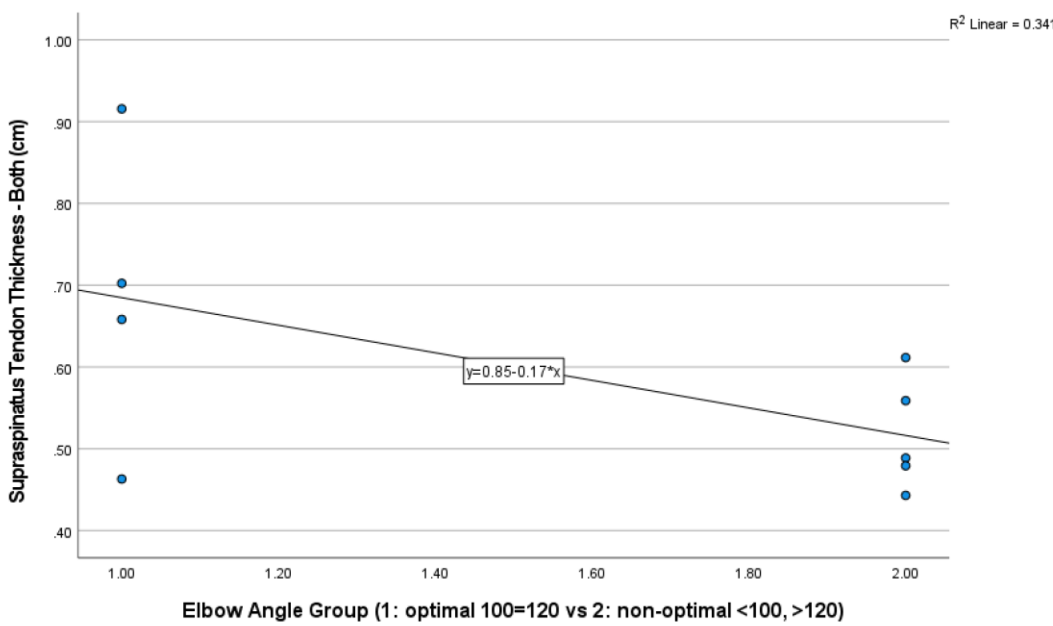


Figure 39: Scatter plot depicting the strong correlation between the use of a non-optimal elbow angle and a smaller supraspinatus tendon thickness.

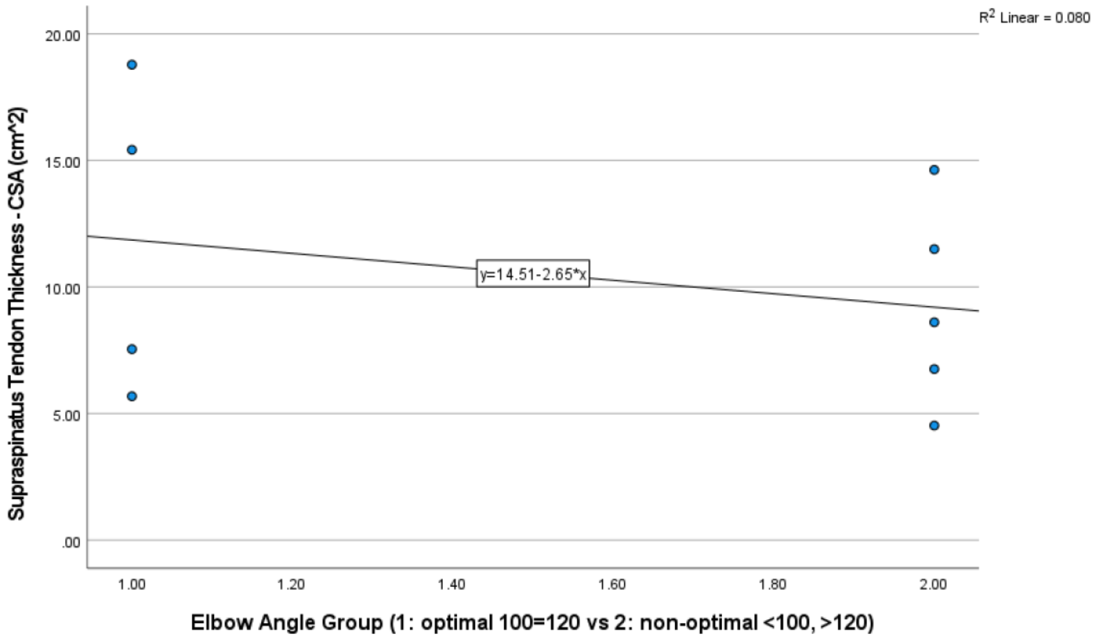


Figure 40: Scatter plot depicting the weak correlation between the use of a non-optimal elbow angle and a smaller supraspinatus CSA.

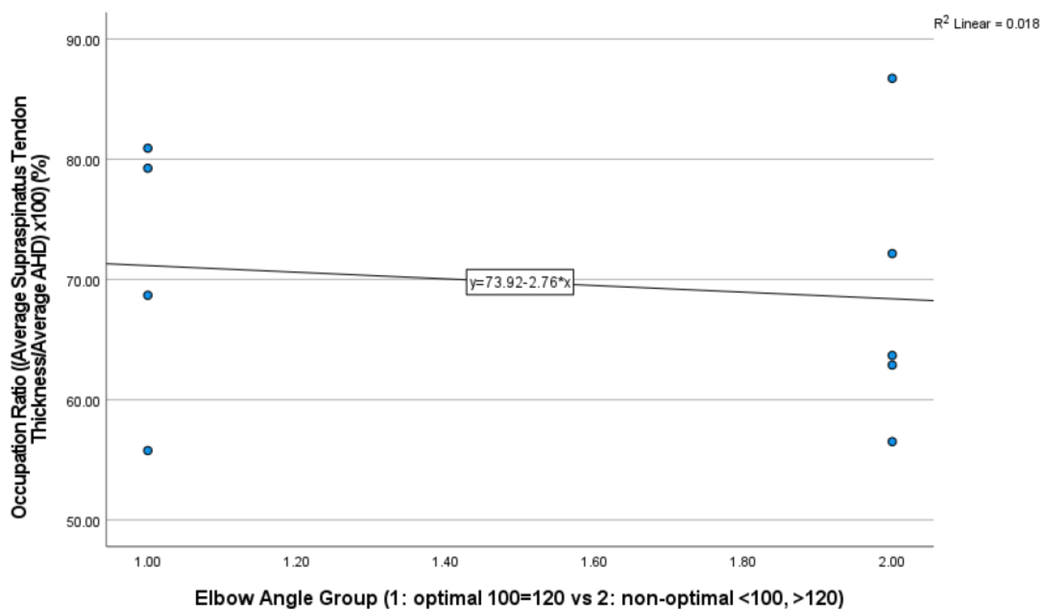


Figure 41: Scatter plot depicting the weak correlation between the use of a non-optimal elbow angle and a smaller supraspinatus tendon occupation ratio.

Aim 4: Pain

Of the 9 participants who participated in this study, 8 completed the pain outcome assessments, so therefore pain correlations were completed with an N = 8. Of the 8 participants who completed the WUSPI assessment, 4 reported shoulder pain (50%). The average WUSPI PC score for all participants was 3.40 +/- 6.36 out of 150. The highest WUSPI PC score recorded was an 18.61, and the lowest WUSPI PC score recorded was a 0. The subject who reported the most pain was 13.9 years old and had their L3 lesion for 13.5 years. Of the 4 subjects who reported pain, 3 of them were over the age of 20, and 3 of them had their SCIs for more than 10 years. The test items with which the participants reported experiencing pain included "pushing your chair for 10 minutes or more", "pushing up ramps or inclines outdoors", "washing your back", "usual activities at work or school", "performing household chores", and "sleeping". The average PROMIS T-score was 45.39 +/- 8.57. PROMIS T-scores were standardized raw scores with a mean of 50 and a standard deviation of 10. The highest PROMIS T-score recorded was a 55.9, and the lowest PROMIS T-score recorded was a 34. WUSPI scores and other outcomes data for all subjects are listed in Table 12.

Table 12: Subject pain and independence outcome scores.

Subject	WUSPI Raw Score (150)	WUSPI PC Score	PROMIS Raw Score (40)	PROMIS T Score	SCIM-III Raw Score (100)
1	0	0	8	34	64
2	0	0	13	46.5	73
3	0	0	12	45.7	52
4	0	0	8	34	68
5	3.94	3.94	12	52.6	61
6	3.47	3.47	16	55.9	74
7	1.03	1.19	8	40.7	73
8	16.13	18.61	20	53.7	72
9	N/A	N/A	N/A	N/A	N/A
Average	3.07	3.40	12.13	45.39	67.13

Seat Angle. It was hypothesized that pediatric MWC users with SCI who used straighter seat angles would have higher levels of shoulder pain as measured by the WUSPI than those with more acute seat angles. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 8 participants' seat angle and their WUSPI score. Only a weak negative correlation was found between seat angle and WUSPI PC score that was insignificant (r=-0.156, p=0.711; r_s =-0.038, p=0.929) (Figure 42). The seat angles used varied across participants who reported experiencing shoulder pain. Although, the individual with the highest WUSPI score had a seat angle of 4.27 degrees, which was below the average seat angle calculated for the entire group (5.16 degrees). The average WUSPI score of those who used a seat angle less than 5 degrees (N=4) was 5.637 +/- 8.848. The average WUSPI score of those who used a seat angle more than 5 degrees (N=4) was 1.17 +/-1.64.

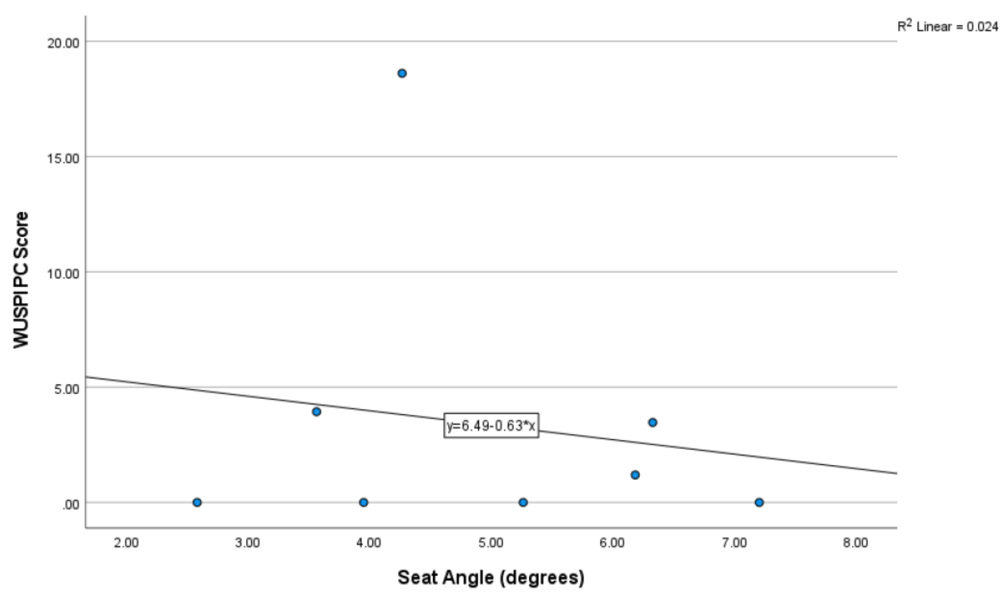


Figure 42: Scatter plot depicting the weak negative correlation between seat angle and WUSPI PC score.

Horizontal Axle Position. It was hypothesized that pediatric MWC users with SCI whose axles were positioned more rearward in the horizontal direction would have higher levels of shoulder pain based on WUSPI PC scores than those with more neutral or more forward axle positions. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 8 participants' horizontal axle position and their WUSPI score. No correlation between ACR x position and WUSPI score was found ($r=0.394$, $p=0.335$; $r_s=0.0$, $p=1.0$) (Figure 43), but when the participants were separated into groups (forward axle position vs rearward axle position) a weak correlation was found between the use of a rearward axle position and an increased WUSPI score that was insignificant ($r=0.162$, $p=0.702$; $r_s=0.067$, $p=0.875$) (Figure 44). Of the 4 participants who reported experiencing shoulder pain on the WUSPI assessment, the 2 with the highest PC scores had more positive ACR x positions when compared to the group (greater than the group average of 69.7 mm), and therefore, more rearward axles. The 2 participants who reported lower levels of pain on the WUSPI had more negative ACR x positions (below the group average), and therefore, more forward axles. The average WUSPI PC score of those who used a forward axle position (N=2) was 1.73 +/- 2.45. The average WUSPI PC score of those who used a more rearward axle position (N=7) was 3.96 +/- 7.34

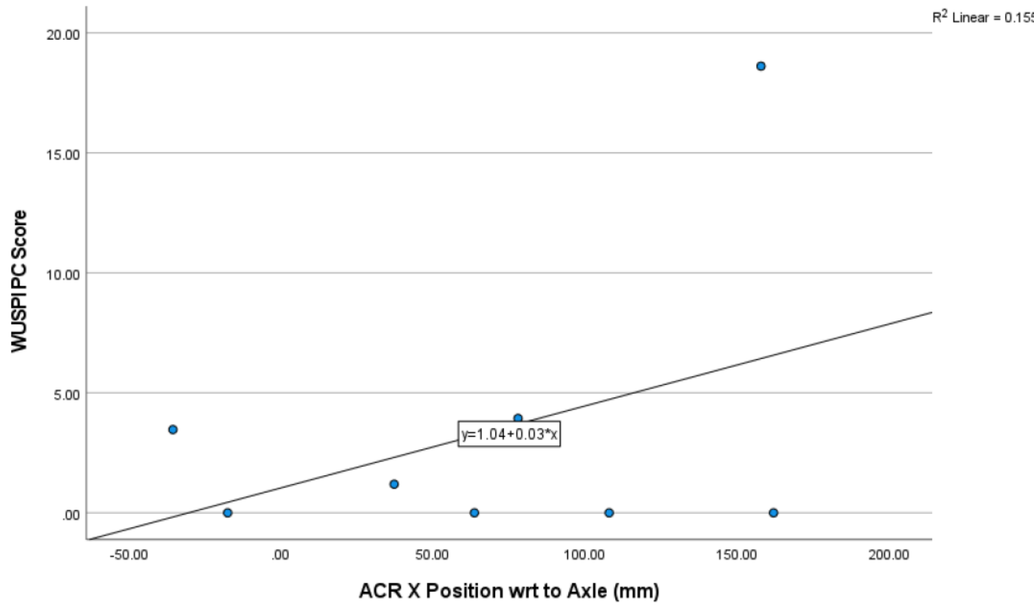


Figure 43: Scatter plot depicting no correlation between ACR x position and WUSPI PC score.

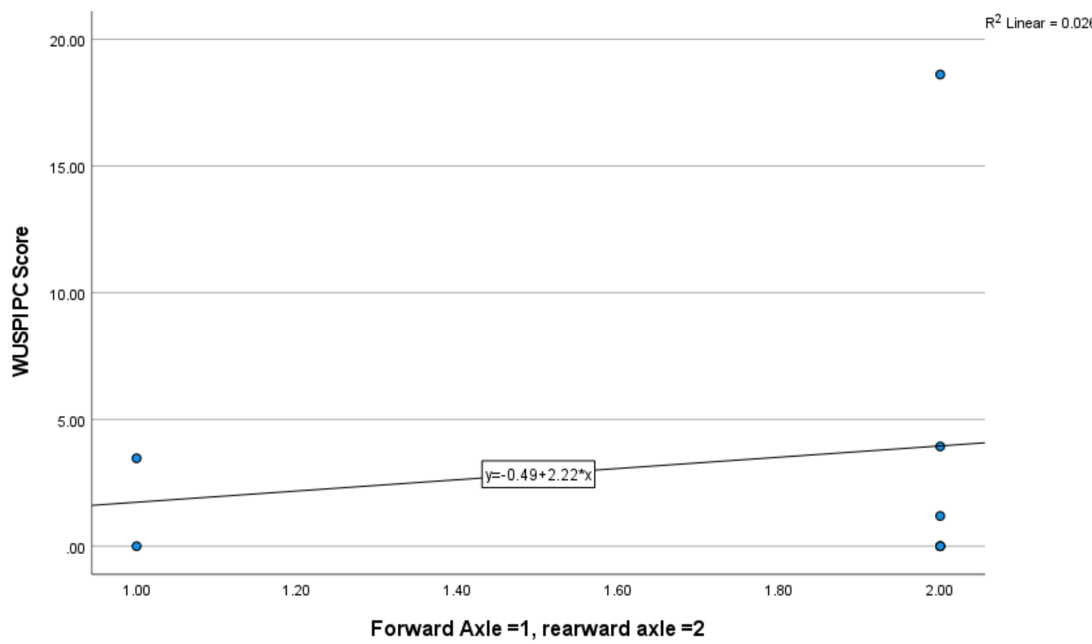


Figure 44: Scatter plot depicting the weak correlation between the use of a rearward axle position and an increased WUSPI PC score.

Vertical Axle Position. It was hypothesized that pediatric MWC users with SCI whose axles were positioned non-optimally in the vertical axis (outside of the 100-120 degrees range) would have higher levels of shoulder pain based on WUSPI PC scores when compared to those with optimal vertical axle positions. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 8 participants' vertical axle position and their WUSPI score. A moderate positive correlation was found between elbow flexion angle and WUSPI PC score that was insignificant ($r=.701$, $p=0.053$; $r_s=0.457$, $p=0.255$) (Figure 45). The participant with the largest elbow flexion angle at top dead center also had the most reported shoulder pain according to the WUSPI.

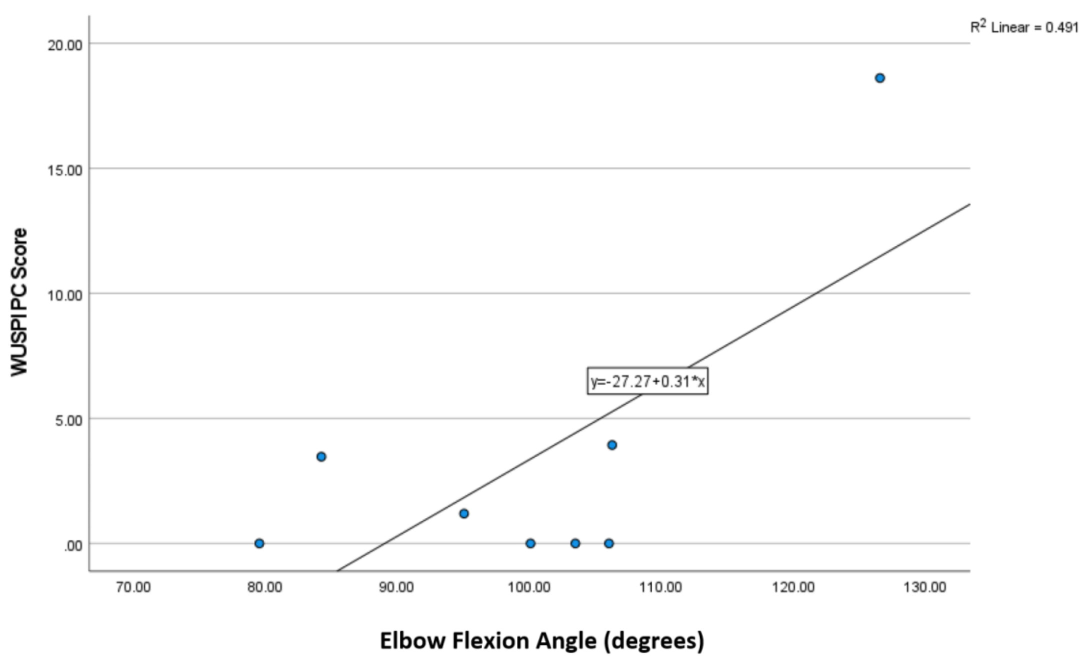


Figure 45: Scatter plot depicting the moderate positive correlation between elbow flexion angle and WUSPI PC score.

When the participants' WUSPI scores were separated into groups (optimal and non-optimal) based on their vertical axle positions, a moderate, but insignificant, correlation was found between the use of a non-optimal angle and a higher WUSPI PC score (r=.407, p=0.318; r_s =0.407, p=0.317) (Figure 46). The average PC score for the optimal group (100-120 degrees of elbow flexion) was 0.98 +/- 0.98. The average PC score for the non-optimal group (<100 or >120 degrees) was 5.82 +/- 4.33. Of the 4 participants who used an optimal vertical axle position based on adult recommendations, only 1 reported experiencing shoulder pain on the WUSPI. Of the 4 participants who used a non-optimal vertical axle position, 3 reported experiencing shoulder pain.

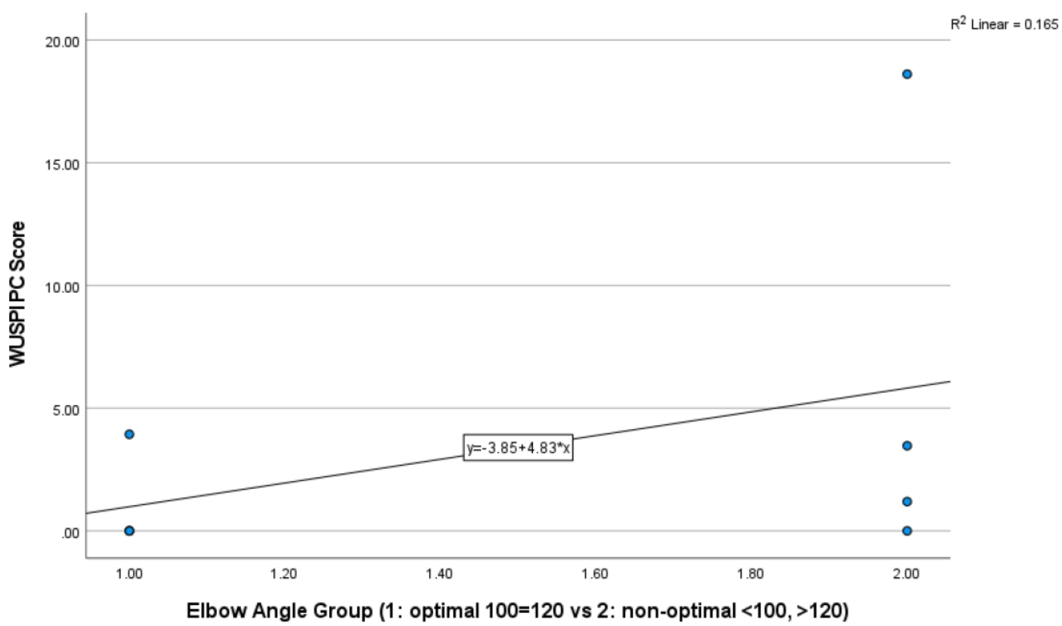


Figure 46: Scatter plot depicting the moderate correlation between the use of a non-optimal elbow angle and a higher WUSPI PC score.

Aim 5: Independence

Similar to the pain outcomes, only 8 participants completed the SCIM-III independence assessment. The average SCIM-III score for all participants was 67.13 +/- 7.72. The highest SCIM-III score recorded was a 74, and the lowest SCIM-III score recorded was a 52. Independence scores for all subjects are listed in Table 12.

Seat Angle. It was hypothesized that pediatric MWC users with SCI who used straighter seat angles would have lower levels of independence as measured by the SCIM-III than those with more acute seat angles. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 8 participants' seat angle and their SCIM-III score. A strong positive correlation between seat angle and SCIM score was found that was insignificant ($r=.431$, $p=0.286$; $r_s=0.695$, $p=0.056$) (Figure 47). The 3 participants with the largest seat angles also had the highest independence scores on the SCIM-III. The average SCIM-III score of those who used a seat angle that was less than 5 degrees (N=4) was 66.25 +/- 4.787. The average SCIM-III score of those who used a seat angle that was more than 5 degrees (N=4) was 68 +/- 10.68.

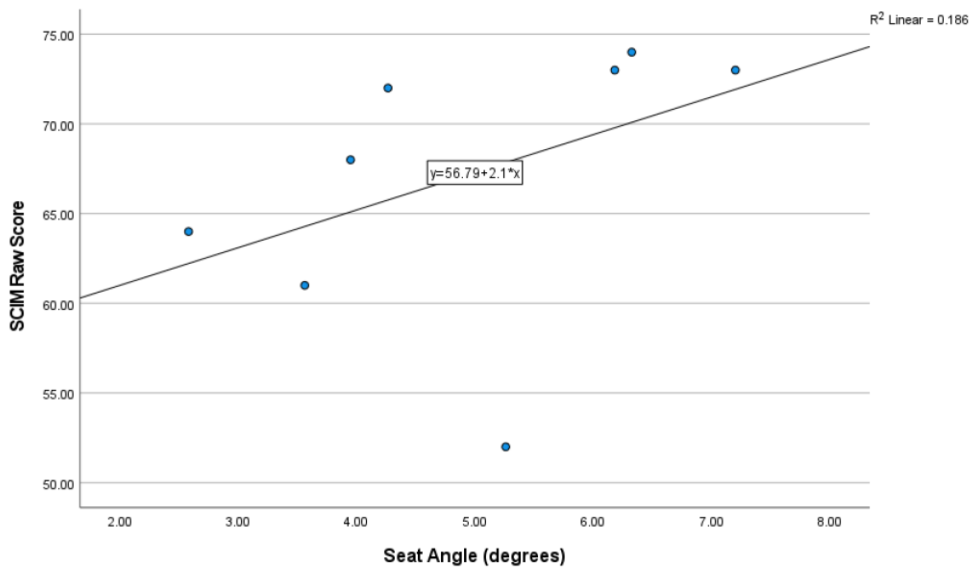


Figure 47: Scatter plot depicting the strong positive correlation between seat angle and SCIM score.

Horizontal Axle Position. It was hypothesized that pediatric MWC users with SCI whose axles were positioned more rearward in the horizontal direction would have lower levels of independence based on SCIM-III scores when compared to those with more neutral or more forward axle positions. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 8 participants' horizontal axle position and their SCIM-III score. No correlation between the horizontal axle position and the SCIM-III score was determined ($r=.304$, $p=0.465$; $r_s=-0.036$, $p=0.933$) (Figure 48). Independence levels varied greatly among the participants based on horizontal axle position. This was most noticeable when looking at the two participants who maintained a forward axle position in relation to the shoulder throughout wheelchair propulsion (the axle position clinically recommended for adults). Of the two participants, one had the lowest recorded SCIM-III score of the group and the other participant had the highest SCIM-III score of the group. The average SCIM-III score of those who used a forward axle position (N=2) was a 63 +/- 11. The average SCIM-III score of those who used a rearward axle position (N=6) was a 68.5 +/- 2.08.

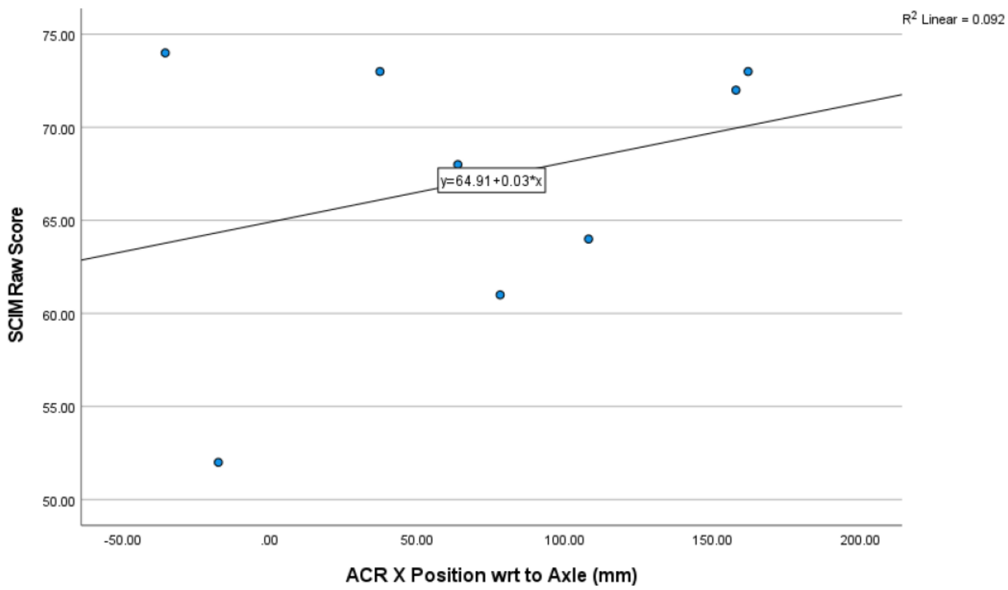


Figure 48: Scatter plot depicting the lack of correlation between horizontal axle position and SCIM-III independence scores.

Vertical Axle Position. It was hypothesized that pediatric MWC users with SCI whose axles were positioned non-optimally in the vertical axis (outside of the 100-120 degrees range) would have lower levels of independence based on SCIM-III scores when compared to those with optimal vertical axle positions. A bivariate-Pearson's correlation and a Spearman's rank order correlation were run to determine the relationship between the 8 participants' vertical axle position and their SCIM-III score. There were no correlations between elbow angle and independence scores ($r=0.337$, $p=0.415$; $r_s=-0.12$, $p=0.778$). Only a weak, insignificant relationship between the use of a non-optimal axle position and increased SCIM-III score was determined when the participants were separated into optimal and non-optimal groups based on elbow angle (r=0.087, p=0.838; r_s =0.274, p=0.511) (Figure 49). The average SCIM-III score for the optimal group (100-120 degrees of elbow flexion) was 66.5 +/- 5.20. The average SCIM-III score for the non-optimal group (<100 or >120 degrees) was 67.75 +/- 10.53. Interestingly, however, the participant with the lowest independence score recorded and 3 of the 4 participants with the highest independence scores recorded utilized a non-optimal vertical axle position based on adult recommendations (<100 or >120 degrees elbow flexion).

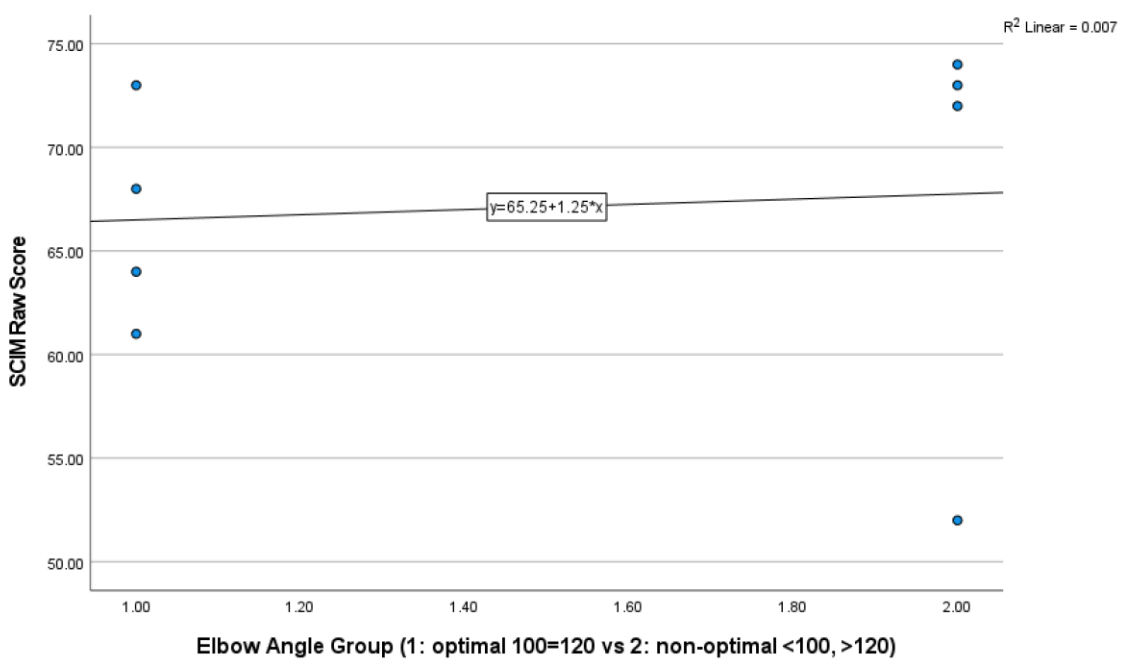


Figure 49: Scatter plot depicting the moderate negative correlation between horizontal axle position and supraspinatus tendon occupation ratio.

Discussion

Comparison of Wheelchair Settings

Clinical guidelines for adult manual wheelchair users recommend that the rear wheel be positioned as far forward as possible while still maintaining stability; these adult guidelines also advise that the seat be vertically adjusted to a position where the user's elbow flexionangle is between 100-120 degrees when the hand is at top-dead center of the pushrim to eliminate stress on the shoulder and allow for optimal grasp during propulsion (Krey & Calhoun, 2004; Michael et al., 2020; Paralyzed Veterans of America Consortium for Spinal Cord, 2005; Slowik & Neptune, 2013) . In addition, a more elevated seat (larger sagittal seat angle) is recommended, as a straight seat angle has shown to reduce pelvic stabilization and increase risk of shoulder pain and pathology in adults (Giner-Pascual et al., 2011; Paralyzed Veterans of America Consortium for Spinal Cord, 2005). Unfortunately, no such recommendations exist for the population of pediatric MWC users, so the wheelchair settings used by the participants in this study were compared to the available adult guidelines.

All of the pediatric MWC users who participated in this study utilized slightly elevated or acute sagittal seat angles. None of the participants used straight seat angles (parallel to the floor), and therefore, the participants in the study followed the adult recommendation of utilizing a larger seat angle to improve pelvic stabilization. This study found that a larger percentage of pediatric participants used an acute seat angle (100%) compared to previous studies with adult populations where only 44% used an acute seat angle on their manual wheelchairs (Giner-Pascual et al., 2011). This may be due to the fact that the wheelchairs used in previous studies had limited settings and could only be adjusted to either the straight position or to 10 degrees of elevation, while the preferred seat angle may in fact be closer to 5 degrees for this population. Further research is needed, however, to determine if the optimal seat angle for ensuring pelvic stabilization and safer shoulder biomechanics is similar in children and adults. The percentage of pediatric MWC users whose wheelchair parameters followed adult guidelines are displayed in Appendix I, 1-2.

Most of the pediatric participants in this study (78%) propelled their wheelchairs with their dominant shoulder positioned in front of their axle, indicating a more rearward axle position. Contrary to adult recommendations, these pediatric participants did not use a forward axle position. More research is needed to determine if a more rearward axle position can negatively increase the rolling resistance, contact angle, stroke frequency, or push forces experienced by children during wheelchair propulsion as they have been found to do with adults (Boninger et al., 2000; Brubaker, 1986; Hughes et al., 1992; Masse et al., 1992).

Finally, a majority of the participants (56%) in this study had their seats non-optimally positioned in the vertical axis based on adult recommendations. More than half of the participants had elbow flexion angles recorded that fell outside of the clinically recommended 100-120 degrees when their hands were at top dead center of the pushrim. If the effects of vertical axle positioning are similar in adults and children, the pediatric participants with elbow flexion angles that were <100 or >120 degrees may be at greater risk of shoulder impingement due to higher push frequencies or decreased mechanical efficiency (Boninger et al., 2000; Van der Woude et al., 1989). More research is needed to determine if the optimal range for the elbow angle based on vertical axle positioning is the same in adults and children.

Comparison of Wheelchair Settings Based on Subject Demographics

Although clinical recommendations exist for optimal wheelchair set up in adults, these recommendations do not take into account the diverse needs of MWC users with different SCI lesion levels, different ages, and different amounts of time since injury. For example, there are currently no wheelchair seating and positioning recommendations specific to the pediatric population (Krey & Calhoun, 2004). Pediatric clinicians may follow the “2 inch rule” by adding 2 inches to the patient’s seat width and subtracting 2 inches from the patient’s seat depth, or they may position the pediatric wheelchair axle under the child’s pelvis to distribute body weight, but, limited evidence supports these recommendations (Krey, 2005). Similarly, those with higher level SCIs (T9 and above) may require larger dump angles to facilitate better sitting posture because they lack the spinal strength to maintain stability without overcompensating at the shoulder (Cloud et al., 2017). Despite this, no adjusted guidelines currently exist for setting up wheelchairs for individuals with various SCI lesion levels.

The current study found no significant difference in seat angle based on SCI lesion level, but weak correlations did exist relating lower SCI lesion levels to more rearward axle positions and increased elbow flexion angles. These limited findings may be due to the fact that no participants with cervical SCIs were included in this study. As was expected, participants used different seat angles and axle positions based on their ages. As the participants’ ages increased, they were more likely to use a larger seat angle, a more forward axle position, and a non-optimal elbow angle, however, of the pediatric MWC users who participated in this study, the youngest and the oldest of the participants were interestingly the only two subjects to maintain the recommended forward axle position during wheelchair propulsion. Similarly, participants used different seat angles and axle positions based on the time that had passed since their injury (Appendix I, 3-4). As the participants' time since injury increased, they became more likely to have a larger seat angle, maintain a more forward axle position, and use a less optimal elbow flexion angle when their hands were at top dead center of the pushrim. These findings may indicate that clinicians are currently being forced to make one of two decisions when prescribing a MWC to a child with SCI: 1) choose to properly fit the child's initial wheelchair to their body by following adult clinical recommendations, but as the child ages and enters puberty their chair may no longer fit them, and they may have to wait before they can receive a larger chair, or 2) choose to provide the child with a slightly larger wheelchair than what is necessary, so that they can grow into it, but then the child will have to use an inappropriately fitted device as they are first learning wheelchair skills. Both scenarios are less than ideal, but with limited funding and limited adjustability in current MWCs, clinicians may be forced to decide if their patients are going to use an ill-fitting wheelchair as a child or use an ill-fitting wheelchair as an emerging adult. Alternatively, these findings may also indicate that the adult clinical recommendations for wheelchair settings do not adequately meet the needs of the pediatric population.

Comparison of Shoulder Pathology & Tendon Thickness

In previous research studies, AC joint narrowing, AC degenerative joint disease, acromial edema, distal clavicular edema, coracoacromial ligament edema, and biceps tendonitis have been highly prevalent in the shoulders of adult MWC users (Boninger et al., 2001; Finley & Rodgers, 2004; Lal, 1998; Mercer et al., 2006). In adult populations, anywhere from 58-100% of MWC users have been found to have shoulder abnormalities (Morrow et al., 2014).

In the current pediatric study, 44% of the participants had tendinopathies identified using ultrasound, including AC join osteophytes, subacromial bursitis, AC joint effusion, supraspinatus tendonitis, and biceps tenosynovitis (Appendix I, 5). Of the painful shoulders that were imaged (N=4), 75% of them had tendinopathies identified, which is similar to previous studies that have looked at the prevalence of pathologies in painful adult shoulders (Morrow et al., 2014). No tears were identified in the pediatric shoulders imaged in this study. Fewer participants in this study had shoulder tendinopathies than has been reported in adult populations, which may be due to the fact that younger participants are more resilient and better suited to overcome the stresses placed on the shoulder during wheelchair propulsion (Sawatzky et al., 2005; Zebracki et al., 2010). It is important to note, however, that even though fewer pediatric MWC users in this study had shoulder pathologies than what has been reported in adults, it is still concerning that, already at an early age, these children are experiencing pain and pathology to such a significant extent.

Changes in supraspinatus tendon thickness, cross-sectional area, and occupation ratio can signify potential risk factors in the adult population. For the adult population, a decrease in supraspinatus tendon occupation ratio can indicate supraspinatus atrophy (Morag et al., 2006) while an increase in tendon thickness can signify muscle overuse in adult MWC users (Belley et al., 2017). Based on the adult recommendations, a wheelchair with an acute seat angle, a more forward axle position, and an optimal vertical axle position can eliminate dangerous wheelchair propulsion, and therefore, reduce the risk of shoulder pathologies, such as supraspinatus tendon inflammation or degeneration (Boninger et al., 2000; Freixes et al., 2010; Giner-Pascual et al., 2011; Gorce & Louis, 2012; Hughes et al., 1992; Kotajarvi et al., 2004; Van der Woude et al., 1989). As expected, participants in this study who used wheelchairs with larger sagittal seat angles or more elevated seats tended to have smaller supraspinatus tendons, while those who used straighter seat angles or flatter wheelchair seats, compared to their peers, tended to have larger supraspinatus tendons (Appendix I, 6). This may indicate that those who use straighter seat angles are more at risk of tendon inflammation because of overuse, which is consistent with previous findings in adult populations (Giner-Pascual et al., 2011). Based on these findings, the adult recommendation to avoid straight seat angles may potentially be applied to the pediatric population as well to reduce the risk of shoulder injury. Contrary to what was hypothesized, however, participants with more positive ACR x positions or more rearward axle positions tended to have smaller occupation ratios. This may signify that individuals with more rearward axle positions are actually at risk of tendon degeneration rather than tendon inflammation, which was hypothesized. This could also indicate that the adult clinical guidelines for wheelchair set up are not, in fact, appropriate for pediatric MWC users. Similarly, participants who used a non-optimal elbow angle based on adult recommendations tended to have smaller supraspinatus tendons as measured by thickness, CSA, and occupation ratio. Again, this was not what was expected, and therefore, may indicate that pediatric groups are at a higher risk of tendon degeneration, or that the adult recommendations are not appropriate for reducing risk of pathology in children. Another potential explanation for these findings may just be that pediatric MWC users are more physically resilient to injury and stress than their adult counterparts, which is why they have not yet developed visible pathologies in the shoulder (Sawatzky et al., 2005; Zebracki et al., 2010). Further research studies with larger sample sizes are needed to determine if wheelchair settings do, in fact, have an effect on shoulder pathology.

Comparison of Pain

Several studies have reported the presence of shoulder pain in adult MWC users to be anywhere from 30-80%, but far fewer studies have been able to quantify shoulder pain in the pediatric population (Alm et al., 2008; Curtin et al., 2017; Ferrero et al., 2015; Sawatzky et al., 2005). In studies with smaller sample sizes, anywhere from 16-26% of pediatric MWC users have reported shoulder pain (Schottler et al., 2019) (Roehrig & Like, 2008), but overall the prevalence of shoulder pain is thought to be far less in pediatric populations than it is for adult MWC users (Sawatzky et al., 2005).

In the current study, 50% of the participants reported experiencing some level of shoulder pain in the last week, however, the average WUSPI PC score for all participants was only 3.4015 +/- 6.357, so the pain intensities reported were relatively low (Appendix I, 7-8). The percentage of participants who reported pain in this study was higher than what has been reported in previous pediatric studies, which may be due to the fact that this study included individuals up to the age of 21 years old. For example, of the 4 subjects who reported pain in our study, 3 of them were over the age of 20. Only 20% of the participants under the age of 18 reported experiencing shoulder pain, which is more in line with previous studies that looked at the prevalence of shoulder pain in pediatric MWC users via the WUSPI (Roehrig & Like, 2008; Schottler et al., 2019).

To prevent pain and pathology in MWC users with SCI, the Paralyzed Veterans of America Consortium for Spinal Cord has created a list of clinical recommendations for the adult population to follow. Based on these guidelines and previous research studies, it is recommended that a wheelchair with an acute seat angle, a more forward axle position, and an optimal vertical axle position be used to eliminate dangerous wheelchair propulsion, and therefore, reduce the risk of shoulder pain (Boninger et al., 2000; Freixes et al., 2010; Giner-Pascual et al., 2011; Gorce & Louis, 2012; Hughes et al., 1992; Kotajarvi et al., 2004; Van der Woude et al., 1989). Previous studies have found that a straight seat angle, a rearward axle position, and a non-optimal vertical axle position can lead to extreme joint positions, increased forces, and increased frequencies of repetitive tasks in adult MWC users with SCI, which can increase the risk of upper extremity pain in this population. (Boninger et al., 2000; Giner-Pascual et al., 2011; Medola et al., 2014).

As expected, the pediatric MWC users in this study who used straighter seat angles tended to have slightly higher WUSPI scores. Similarly, the individuals with the more rearward axle positions also had slightly higher WUSPI scores. Finally, the individuals with non-optimal vertical axle positioning tended to have higher WUSPI scores as well. Although these were weak to moderate correlations due to a smaller sample size, it was apparent that the participants in this study who did not follow adult clinical guidelines for wheelchair setup reported higher levels of shoulder pain on the WUSPI. This may indicate that the adult wheelchair recommendations can also be applied to the pediatric population in order to reduce the prevalence of shoulder pain in this population. The average WUSPI scores of the pediatric subjects based on their wheelchair parameters are listed in Appendix I, 9.

Comparison of Independence

In previous studies, the average SCIM-III independence scores for adults with SCI have been reported as anywhere from 42 to 50 (Ackerman, 2009; Fekete, 2012). In the current study, the average SCIM-III score for the pediatric MWC users with SCI was 67.125 +/- 7.717 (Appendix I, 10). The highest SCIM-III score recorded was a 74, and the lowest SCIM-III score recorded was a 52. This study may have found higher average SCIM-III independence scores because the participants were asked to complete the questionnaire on their own whereas previous studies had a clinician observe the participants as they performed the items and score the assessment based on their performance. Participants in this study may have reported their independence levels as slightly higher than they actually are.

Adult MWC users with decreased range of motion and increased shoulder pain due to repetitive strain have reported lower than average independence scores on both the FIM and the CHART in previous studies (Ballinger et al., 2000). This signifies that shoulder pain and decreased function as a result of SCI and repetitive wheelchair population may prevent MWC users from independently completing their ADLs, navigating their environment, and participating in their community (Ballinger et al., 2000). As mentioned above, clinical recommendations for adult MWC users include the use of a wheelchair that has an acute sagittal seat angle, a more forward axle, and an optimal vertical axle position. It has been demonstrated that, by following these guidelines, adult MWC users are more likely to preserve their upper extremity function and avoid dangerous joint positions during wheelchair propulsion (Paralyzed Veterans of America Consortium for Spinal Cord, 2005). Based on this information, it is assumed that an appropriately fitted wheelchair that follows these clinical recommendations could improve the user's experience, and therefore, increase an individual's functional independence, comfort, participation, and overall quality of life (Chaves et al., 2004; Di Marco et al., 2003).

Based on statistical analyses, individuals with larger seat angles were much more likely to have higher independence scores on the SCIM-III when compared to those with straighter seat angles (Appendix I, 11). These findings agree with what was hypothesized and with the adult clinical recommendations to use an acute sagittal seat angle. This may indicate that the adult clinical recommendation to use an elevated seat angle can be applied to pediatric MWC users with SCI as well in order to increase their independence levels. Contrary to what was hypothesized, however, there was no relationship between the horizontal axle position and the SCIM-III independence score. This may be due to the fact that of the two participants who maintained forward axle positions during wheelchair propulsion, one had the lowest recorded SCIM-III score of the group and the other participant had the highest SCIM-III score of the group. Interestingly, the individual with the lowest SCIM-III score was also the youngest participant, and the individual with the highest SCIM-II score was also the oldest participant. Upon further analysis, it was discovered that there was a moderate positive correlation between age and SCIM-III independence scores ($r=0.38$, $p=0.353$; $r_s=0.491$, $p=0.217$) (Figure 50) as well as a strong, and significant, positive correlation between time since injury and SCIM-III independence scores ($r=0.717$, $p=0.045$; $r_s=0.85$, $p=0.007$) (Figure 51). This indicates that the participant's age and their time since injury may have been stronger predictors of SCIM-III independence scores than their wheelchair axle position.

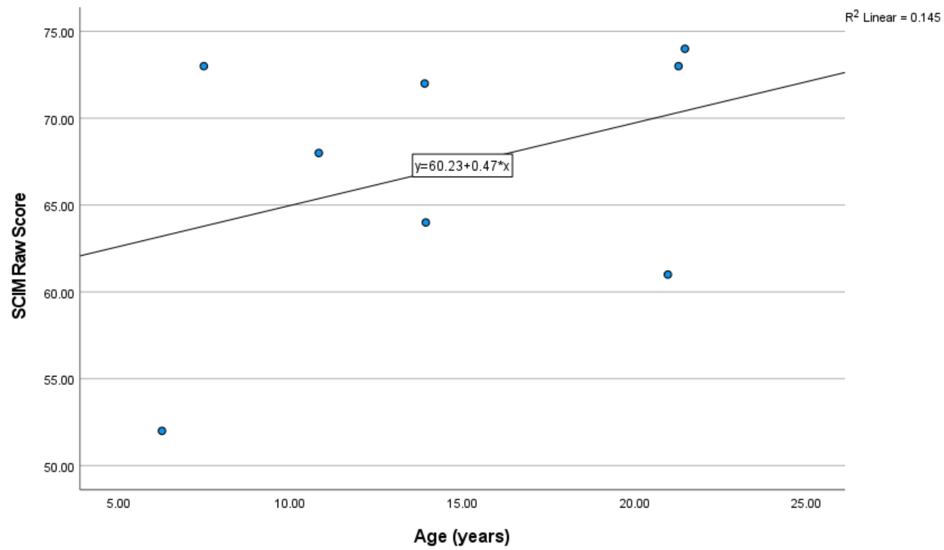


Figure 50: Scatter plot depicting the moderate positive correlation between age and SCIM-III scores.

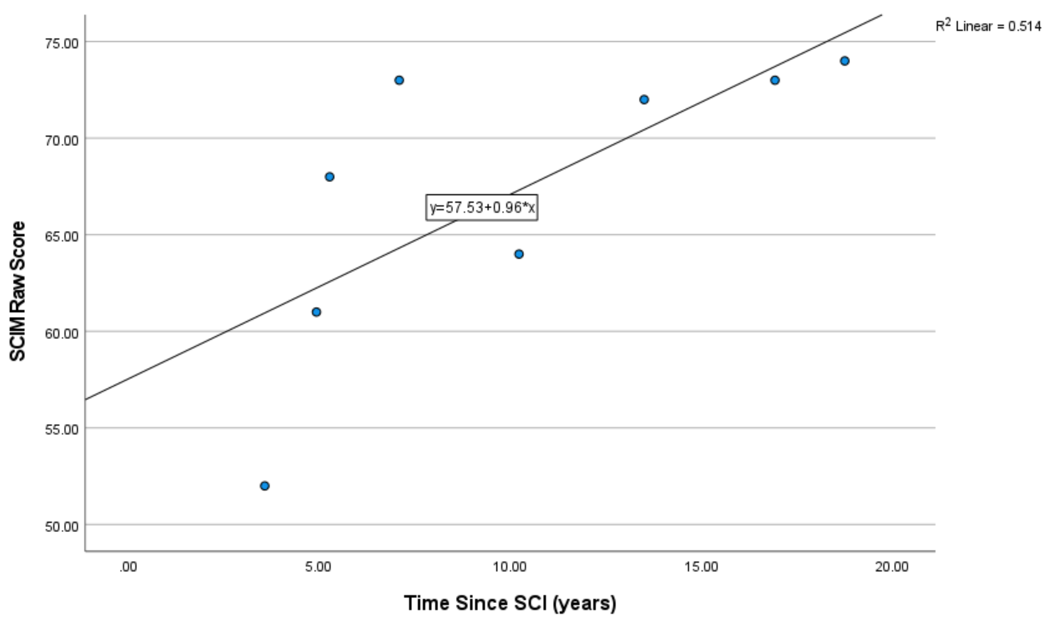


Figure 51: Scatter plot depicting the strong positive correlation between time since injury and SCIM-III independence scores.

Conclusion

Based on the findings of this study, children and young adults who use a MWC for functional mobility tend to use a wide variety of wheelchair settings that may contribute to their risk of shoulder pathology and pain. Not all pediatric MWC users employ the seat and axle positions that have been clinically recommended for use in adult populations, and this may negatively impact their shoulder health, pain experiences, and independence levels. This demonstrates the potential need for clinicians to develop pediatric specific wheelchair guidelines and recommendations for preserving upper extremity function. The physical limitations, daily occupations, and environmental challenges experienced by MWC users vary greatly among the pediatric and adult populations, so we should assume that the clinical recommendations for maintaining upper extremity function during wheelchair propulsion may also be different between these two groups. More research is needed to determine if the adult clinical guidelines for wheelchair set up and use should also be applied to the pediatric population.

The participants in this study used elevated seat angles, more rearward axle positions, and non-optimal vertical axle positions based on adult recommendations, but the age of the participant and the time since their injury greatly influenced the wheelchair settings they utilized. A significant percentage of these participants (44%) had identifiable shoulder pathologies and an even larger percentage reported experiencing some level of shoulder pain during their daily activities (50%). This demonstrates the need for clinicians to educate pediatric MWC users on proper wheelchair propulsion mechanics, activity modifications to reduce stress, and pain management techniques to avoid increased shoulder pain and pathology.

Participants who used straighter seat angles had larger supraspinatus tendons than those who used more elevated seat angles. Similarly, participants who used non-optimal vertical axle positions, violating adult clinical guidelines, reported higher levels of shoulder pain. Independence scores were less dependent on wheelchair settings and more dependent on the age of the participant, but individuals who used a straighter seat angle tended to have lower independence scores. This demonstrates the need for clinicians to focus on adjusting client wheelchair settings throughout the lifespan, and to continue wheelchair training with children as they grow and transition into adulthood.

Prior to wheelchair selection and use, children and their caregivers need to be adequately informed of the available MWC options and the potential effects of the various wheelchair settings on their comfort and function

. In addition, clinicians need to regularly check in with their clients to ensure that wheelchair seating needs have not changed as the child grows and develops. Finally, clinicians need to advocate for more adjustable wheelchairs and better funding for mobility devices, so that pediatric MWC users entering puberty or adulthood do not have to wait to receive a chair that will better reduce their risk of shoulder pathology and pain in the future.

Fortunately, occupational therapists are uniquely suited to oversee these pediatric MWC concerns as they have been trained to understand the plethora of environmental and interpersonal demands these children face in the school, community, and rehabilitation settings. Occupational therapists address the assistive technology needs of their clients as they relate to occupational performance and participation, and they ensure that those needs continue to be met across the lifespan. The findings of this study can provide occupational therapists with valuable information about the wheelchair settings that are currently being used by pediatric MWC users, the prevalence of shoulder pain and pathology in this population, the effects of different wheelchair parameters on health outcomes, and how the relative fit of the MWC may change as the child ages (Figure 52). With this information, occupational therapists may be better able to reduce the risk of shoulder pain and pathology in MWC users by developing appropriate clinical guidelines and training methods for proper wheelchair set up and use in the pediatric population.

Advocate	Advocate for more adjustable MWCs and better funding for mobility devices
Develop	Develop clinical guidelines and recommendations for pediatric MWC users with SCI
Educate	Educate on proper propulsion mechanics, activity modifications, and appropriate wheelchair settings
Optimize	Optimize seating and positioning for comfort and performance
Lead	Lead wheelchair skills training to optimize UE function and avoid dangerous positions
Facilitate	Facilitate participation in meaningful activities & encourage independence with ADLs/IADLs
Develop	Develop interventions to support social participation, play, and appropriate childhood development
Introduce	Introduce pain management techniques
Adjust	Adjust wheelchair settings & train users throughout the lifespan as they grow and transition into adulthood

Figure 52: Table listing the clinical implications of this study and its connection to occupational therapy

Future Directions

It is unknown whether current adult clinical guidelines for wheelchair set up and use can be applied to the pediatric population. Future work with MWC users with SCI should include the development of pediatric specific clinical guidelines for the preservation of upper extremity function during wheelchair propulsion. Clinical guidelines should include recommendations for wheelchair propulsion techniques and proper wheelchair set up to reduce the risk of pain and pathology in the pediatric population.

In the current study, there were a total of 9 participants ages 6-21 years old. To significantly determine the effects of wheelchair settings on pain and pathology, future studies should include a larger sample size with pediatric participants who are closer in age. Another limitation of this study was its descriptive design. Because participants used their own wheelchairs during data collection, it was difficult to establish functional relationships between different wheelchair settings and functional outcomes. In the future, pediatric participants should be recruited based on the wheelchair settings they currently use. For example, participants who use a straight seat angle and participants who use a seat angle > 10 degrees should be recruited, and once a large enough sample size has been recruited, the pain scores could be compared between the two groups. The research design could also be adjusted to be an ABAB comparative study. For example, the participants could have propelled a wheelchair with a forward axle position and then propelled a wheelchair with a rearward axle position and the joint angles or forces applied to the pushrim could have been compared across each phase.

Similarly, the current study defined the vertical axle position as either optimal or non-optimal based on the elbow flexion angle. The elbow angle was calculated by finding the planar sagittal angle between the acromion process, the olecranon process, and the ulnar styloid. To more accurately reflect the goniometric measurement used by clinicians for the elbow flexion angle, future studies may want to use the lateral epicondyle marker rather than the olecranon process marker when calculating this angle.

The outcomes measures used to assess pain and independence in pediatric MWC users could also be adjusted in future studies to accommodate for study limitations. In the current study, participants completed the SCIM-III assessment on their own or with their legal guardian. Future work could have a clinician complete the assessment to ensure more accurate independence scores. Similarly, the WUSPI was used in this study to calculate shoulder pain in the pediatric population, but future studies could look at the PROMIS or other pain assessments that have been validated with children. It may even be beneficial to look at the effects of wheelchair settings on participant satisfaction using the Satisfaction with Life Scale as this measure may be less dependent on age than the independence scores.

Finally, supraspinatus tendon thickness, the chosen variable for correlating shoulder tendinopathies in this study, was not found to be the strongest predictor for pathology. Future studies could normalize tendon thickness measurements to subject height, weight, or body mass index to better determine if participants were experiencing tendon degeneration or inflammation.

In summary, this work supports the need for pediatric specific clinical guidelines surrounding wheelchair use and set up. Future work with the pediatric population should investigate the effects of different wheelchair settings that are known to affect the upper extremity biomechanics and wheelchair propulsion techniques in the adult population. In addition, future research studies should determine if the biomechanical demands of wheelchair propulsion, such as the forces, moments, and join angles, change with the use of different wheelchair settings as they do in the adult population. Continued work could even look at the effects of other variables like previous device use and level of training on wheelchair settings and other health outcomes in the pediatric population.

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V. Appendices

Appendix A: Wheelchair Users Shoulder Pain Index (WUSPI)

Subject ID: ________________ **Test Date:** ______________

WHEELCHAIR USERS SHOULDER PAIN INDEX

Place an "**X**" on the scale to estimate your level of pain with the following activities. Check box at right if the activity was not performed **in the past week.**
Based on your experiences in the past week, how much shoulder pain do you experience when:

				not performed
1. transferring from a bed to a wheelchair?	No Pain [ ]	______________________________	Worst Pain Ever Experienced	[ ]
2. transferring from a wheelchair to a car?	No Pain [ ]	______________________________	Worst Pain Ever Experienced	[ ]
3. transferring from a wheelchair to the tub or shower?	No Pain [ ]	______________________________	Worst Pain Ever Experienced	[ ]
4. loading your wheelchair into a car?	No Pain [ ]	______________________________	Worst Pain Ever Experienced	[ ]
5. pushing your chair for 10 minutes or more?	No Pain [ ]	______________________________	Worst Pain Ever Experienced	[ ]
6. pushing up ramps or inclines outdoors?	No Pain [ ]	______________________________	Worst Pain Ever Experienced	[ ]
7. lifting objects down from an overhead shelf?	No Pain [ ]	______________________________	Worst Pain Ever Experienced	[ ]
8. putting on pants?	No Pain [ ]	______________________________	Worst Pain Ever Experienced	[ ]
9. putting on a t-shirt or pullover?	No Pain [ ]	______________________________	Worst Pain Ever Experienced	[ ]
10. putting on a button down shirt?	No Pain [ ]	______________________________	Worst Pain Ever Experienced	[ ]
11. washing your back?	No Pain [ ]	______________________________	Worst Pain Ever Experienced	[ ]
12. usual daily activities at work or school?	No Pain [ ]	______________________________	Worst Pain Ever Experienced	[ ]
13. driving?	No Pain [ ]	______________________________	Worst Pain Ever Experienced	[ ]
14. performing household chores?	No Pain [ ]	______________________________	Worst Pain Ever Experienced	[ ]
15. sleeping?	No Pain [ ]	______________________________	Worst Pain Ever Experienced	[ ]

Appendix B: PROMIS Pediatric Pain Interference - Short Form

Subject ID:__________________ Test Date: ____________

PROMIS® Pediatric Item Bank v2.0 – Pain Interference – Short Form 8a

Pediatric Pain Interference – Short Form 8a

Please respond to each question or statement by marking one box per row.

	In the past 7 days…	Never	Almost Never	Sometimes	Often	Almost Always
1698bR1r	I felt angry when I had pain	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
2035R1r	I had trouble doing schoolwork when I had pain..	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
3793R1r	I had trouble sleeping when I had pain	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
9004r	It was hard for me to pay attention when I had pain...	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
2045R1r	It was hard for me to move quickly when I had pain..	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
2049R1r	It was hard for me to move one block when I had pain...	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
1703R1r	It was hard to have fun when I had pain	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
2180R1r	It was hard to stay standing with aid when I had pain...	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

Appendix C: PROMIS Adult Pain Interference - Short Form

Subject ID: ________________ Test Date: ____________________

Adult Pain Interference – Short Form 8a

Please respond to each question or statement by marking one box per row.

	In the past 7 days…	**Not at all**	**A little bit**	**Somewhat**	**Quite a bit**	**Very much**
PAININ9	How much did pain interfere with your day to day activities?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
PAININ22	How much did pain interfere with work around the home?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
PAININ31	How much did pain interfere with your ability to participate in social activities?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
PAININ34	How much did pain interfere with your household chores?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
PAININ12	How much did pain interfere with the things you usually do for fun?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
PAININ36	How much did pain interfere with your enjoyment of social activities? ...	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
PAININ3	How much did pain interfere with your enjoyment of life?......................	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
PAININ13	How much did pain interfere with your family life?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

Appendix D: Spinal Cord Independence Measure (SCIM)

Subject ID: _____________ Test Date: _____________

SCIM-SPINAL CORD INDEPENDENCE MEASURE

Self-Care

1. Feeding (cutting, opening containers, pouring, bringing food to mouth, holding cup with fluid)

0. Needs parenteral, gastrostomy, or fully assisted oral feeding
1. Needs partial assistance for eating and/or drinking, or for wearing adaptive devices
2. Eats independently; needs adaptive devices or assistance only for cutting food and/or pouring and/or opening containers
3. Eats and drinks independently; does not require assistance or adaptive devices

2. Bathing (soaping, washing, drying body and head, manipulating water tap). **A-upper body; B-lower body**

A. 0. Requires total assistance

1. Requires partial assistance
2. Washes independently with adaptive devices or in a specific setting (e.g., bars, chair)
3. Washes independently; does not require adaptive devices or specific setting (not customary for healthy people) (adss)

B. 0. Requires total assistance

1. Requires partial assistance
2. Washes independently with adaptive devices or in a specific setting (adss)
3. Washes independently; does not require adaptive devices (adss) or specific setting

3. Dressing (clothes, shoes, permanent orthoses: dressing, wearing, undressing). **A-upper body; B-lower body**

A. 0. Requires total assistance

1. Requires partial assistance with clothes without buttons, zippers or laces (cwobzl)
2. Independent with cwobzl; requires adaptive devices and/or specific settings (adss)
3. Independent with cwobzl; does not require adss; needs assistance or adss only for bzl
4. Dresses (any cloth) independently; does not require adaptive devices or specific setting

B. 0. Requires total assistance

1. Requires partial assistancewith clothes without buttons, zipps or laces (cwobzl)
2. Independent with cwobzl; requires adaptive devices and/or specific settings (adss)
3. Independent with cwobzl without adss; needs assistance or adss only for bzl
4. Dresses (any cloth) independently; does not require adaptive devices or specific setting

4. Grooming (washing hands and face, brushing teeth, combing hair, shaving, applying makeup)

0. Requires total assistance
1. Requires partial assistance
2. Grooms independently with adaptive devices
3. Grooms independently without adaptive devices

Respiration and Sphincter Management

5. Respiration

0. Requires tracheal tube (TT) and permanent or intermittent assisted ventilation (IAV)
2. Breathes independently with TT; requires oxygen, much assistance in coughing or TT management
4. Breathes independently with TT; requires little assistance in coughing or TT management
6. Breathes independently without TT; requires oxygen, much assistance in coughing, a mask (e.g., peep) or IAV (bipap)
8. Breathes independently without TT; requires little assistance or stimulation for coughing
10. Breathes independently without assistance or device

Subject ID: _____________ Test Date: _____________

6. Sphincter Management - Bladder

0. Indwelling catheter
3. Residual urine volume (RUV) > 100cc; no regular catheterization or assisted intermittent catheterization
6. RUV < 100cc or intermittent self-catheterization; needs assistance for applying drainage instrument
9. Intermittent self-catheterization; uses external drainage instrument; does not need assistance for applying
11. Intermittent self-catheterization; continent between catheterizations; does not use external drainage instrument
13. RUV <100cc; needs only external urine drainage; no assistance is required for drainage
15. RUV <100cc; continent; does not use external drainage instrument

7. Sphincter Management - Bowel

0. Irregular timing or very low frequency (less than once in 3 days) of bowel movements
5. Regular timing, but requires assistance (e.g., for applying suppository); rare accidents (less than twice a month)
8. Regular bowel movements, without assistance; rare accidents (less than twice a month)
10. Regular bowel movements, without assistance; no accidents

8. Use of Toilet (perineal hygiene, adjustment of clothes before/after, use of napkins or diapers).

0. Requires total assistance
1. Requires partial assistance; does not clean self
2. Requires partial assistance; cleans self independently
4. Uses toilet independently in all tasks but needs adaptive devices or special setting (e.g., bars)
5. Uses toilet independently; does not require adaptive devices or special setting)

Mobility (room and toilet)

9. Mobility in Bed and Action to Prevent Pressure Sores

0. Needs assistance in all activities: turning upper body in bed, turning lower body in bed, sitting up in bed, doing push-ups in wheelchair, with or without adaptive devices, but not with electric aids
2. Performs one of the activities without assistance
4. Performs two or three of the activities without assistance
6. Performs all the bed mobility and pressure release activities independently

10. Transfers: bed-wheelchair (locking wheelchair, lifting footrests, removing and adjusting arm rests, transferring, lifting feet).

0. Requires total assistance
1. Needs partial assistance and/or supervision, and/or adaptive devices (e.g., sliding board)
2. Independent (or does not require wheelchair)

11. Transfers: wheelchair-toilet-tub (if uses toilet wheelchair: transfers to and from; if uses regular wheelchair: locking wheelchair, lifting footrests, removing and adjusting armrests, transferring, lifting feet)

0. Requires total assistance
1. Needs partial assistance and/or supervision, and/or adaptive devices (e.g., grab-bars)
2. Independent (or does not require wheelchair)

Subject ID: _____________ Test Date: _____________

Mobility (indoors and outdoors, on even surface)

12. Mobility Indoors

0. Requires total assistance
1. Needs electric wheelchair or partial assistance to operate manual wheelchair
2. Moves independently in manual wheelchair
3. Requires supervision while walking (with or without devices)
4. Walks with a walking frame or crutches (swing)
5. Walks with crutches or two canes (reciprocal walking)
6. Walks with one cane
7. Needs leg orthosis only
8. Walks without walking aids

13. Mobility for Moderate Distances (10-100 meters)

0. Requires total assistance
1. Needs electric wheelchair or partial assistance to operate manual wheelchair
2. Moves independently in manual wheelchair
3. Requires supervision while walking (with or without devices)
4. Walks with a walking frame or crutches (swing)
5. Walks with crutches or two canes (reciprocal walking)
6. Walks with one cane
7. Needs leg orthosis only
8. Walks without walking aids

14. Mobility Outdoors (more than 100 meters)

0. Requires total assistance
1. Needs electric wheelchair or partial assistance to operate manual wheelchair
2. Moves independently in manual wheelchair
3. Requires supervision while walking (with or without devices)
4. Walks with a walking frame or crutches (swing)
5. Walks with crutches or two canes (reciprocal waking)
6. Walks with one cane
7. Needs leg orthosis only
8. Walks without walking aids

15. Stair Management

0. Unable to ascend or descend stairs
1. Ascends and descends at least 3 steps with support or supervision of another person
2. Ascends and descends at least 3 steps with support of handrail and/or crutch or cane
3. Ascends and descends at least 3 steps without any support or supervision

16. Transfers: wheelchair-car (approaching car, locking wheelchair, removing arm- and footrests, transferring to and from car, bringing wheelchair into and out of car)

0. Requires total assistance
1. Needs partial assistance and/or supervision and/or adaptive devices
2. Transfers independent; does not require adaptive devices (or does not require wheelchair)

17. Transfers: ground-wheelchair

0. Requires assistance
1. Transfers independent with or without adaptive devices (or does not require wheelchair)

Appendix E: Protocols and Checklists

Overall Protocol Checklist

Prior to Arrival:

_____ Make sure all batteries are charged and documents are compiled and ready to go

a. Smartwheel batteries
b. Camera batteries
c. Vicon Calibration wand
d. Consent/assent, W9, Outcomes printed
e. Electronic DCS in their own subject folder

_____EMG setup
_____Vicon Calibration and setup
_____BTE or Biodex on and calibration
_____Locate SmartWheel and set up laptop

Upon Arrival:

_____Consent/assent and W9
_____Outcomes

a. WUSPI
b. PROMIS
c. PMoP (Ped)
d. PEDI (Ped) or CHART (Adult)
e. Satisfaction with life

_____Physician Outcomes

a. ISCoS
b. SCIM

_____Physician Clinical Exam Form

a. Shoulder Active ROM
b. Shoulder Resistive ROM
c. Clinical Shoulder Special Tests

_____Ultrasound imaging

a. Ultrasound Data Collection Sheet
b. Export images (Instructions in Individual Protocol Instructions folder of eBinder)

_____Subject Measurements
_____Wheelchair Measurements Vicon capture

a. After, place SmartWheel on assessment side

_____EMG placements
_____BTE or Biodex MMT & MVIC data collection

a. Including Vicon EMG captures

_____Marker placements
_____Vicon Static and ROM captures
_____Vicon motion captures (until 10 complete stroke cycles are recorded)
_____Swap SmartWheel side- change side in SW software

_____Vicon motion captures (until 10 complete stroke cycles are recorded)
_____Remove SmartWheel, then perform 6MPT

R01 Data Collection Protocol – SHC

Checklist for the day/night BEFORE data collection.

1. Charge batteries for:
    - 2010 SmartWheel (2)
    - Delsys Trigno EMG Sensors (All)
    - 2010 SmartWheel Laptop
    - Video camera
    - Handheld camera
2. Print all consent/assent documents and prepare electronic data collection sheets
    - Consent/assent
    - W9 form
    - Outcomes (6 total for Adults, 7 for Peds)
    - Electronic data collection – Clinical Exam
    - Electronic data collection – UWM/Shriners US Data Collection Sheet
    - Electronic data collection – Subject Measurements
    - Electronic data collection – Assistive Devices-History of Use
    - Electronic data collection – MMT & MVIC
    - Electronic data collection – Motion Capture
    - Electronic data collection – US Reliability Master Spreadsheet

Checklist for the day of data collection PRIOR TO participant arrival.

Delsys Trigno EMG Setup (before calibration)

1. Make sure all EMG sensors are charged (i.e., green) and USB is plugged into Vicon computer.
2. Attach adhesive backs to EMG sensors #1-8
3. Pair all EMG sensors using Trigno Control Utility
    a. Vicon Nexus software cannot be open while pairing EMG sensors.
    b. If already paired, hold down the button on the corresponding sensor until the utility acknowledges the sensor is on/paired.
    c. Click Pair on the sensor in Trigno Control Utility and simultaneously hold down the button on the corresponding sensor until the utility acknowledges the sensor is paired.
4. Once all EMG sensors are paired, open Vicon Nexus software.

5. Under System >> SmartWheel >> Devices, right-click Add Digital Device >> Add Delsys Trigno System.

Motion Capture Lab

6. Prep the lab space
    - Close wall and blinds
    - Cut tape/prep markers (27 for subject + 17 wc markers + 10 spares) and remove from the capture volume
    - Compile all hard copy documents in subject folder and electronic data collection sheets in electronic folder
    - Compile all tools needed (e.g., tape measurer, digital caliper, goniometer, inclinometer, ultrasound gel, etc.)
7. Turn on Vicon data collection computer and Vicon camera boxes (power switch on back and/or blue power touch symbol on the front)
8. Select System >> SmartWheel
9. Calibrate the Vicon cameras
    - Use the setup walkthrough checklist >>Vicon Camera Calibration<<
    - Set sampling rate to 120 Hz

Biodex

10. Turn on the Biodex using the switch on the back
    - Be sure to remove all attachments prior to turning on the Biodex.
    - Flip switch with Biodex picture on front
11. Turn on the Biodex computer.
12. Press start on the panel to initialize the dynamometer
13. Calibrate the Biodex following the calibration tutorial.
    - File >> Verify Calibration >> Follow on-screen instructions >> Check results
14. Test end ranges of motion (push blue switch that says rotate on attachment board button for upper range and then blue button that says set limit away on main monitor; repeat for lower range using button that says set limit toward.
15. Open the Biodex software on the desktop.
    - Verify that you are in the UWM R01 database

SmartWheel

16. Locate the 2010 SmartWheel and dummy wheel (in the closet)
17. Locate the 2010 SmartWheel gray duffle bag with laptop, cords, and toolkit (in the closet)

Checklist for the day of data collection <u>UPON</u> participant arrival.

1. Greet participant in the lobby of the building and guide to Motion Lab
2. Review study with participant and obtain consent/assent and W9 form
    - Make photocopy for participant to keep
3. Administer pain and quality of life outcomes
4. If needed, ask participant to change clothing for data collection
5. A) <u>One researcher</u> will assist Dr. Mukherjee with recording SCIM/ISCoS, clinical exam, and ultrasound imaging findings
    - Record data in the >>SCIM<< and >>ISCoS<< outcomes documents
    - Record data in the >>Clinical Exam Form<<
    - Record both image order and the presence of pathology using the >>SHC-US DCS<<
    - Determine shoulder for EMG assessment

   B) <u>One researcher</u> will set up participant file in Biodex software

    - Use database manager to create new participant document for every study (copy on in active database and edit name/settings for current study)
    - Set Protocol (second button from the top on the left side of the screen)
        - Select Unilateral >> Isometric >> Shoulder >> 5s Contraction Time >> 3 Reps
    - If machine gets locked, return to setup and reset ROM
    - Ensure the red mark on the attachment lines up with the mark on the drum (R for right, L for left)
    - Create/Find Patient (top left button on screen) >> choose Protocol
    - Set range of motion (clear limits on screen)
    - Take AROM for participant (toward and away), then click on the goniometer button
    - Set up protocol such that anatomical reference is set at neutral/starting position
        - Ex: 0 degrees for neutral position for internal and external rotation
    - Select Curve Analysis view to look at info for each trial (Enable Cursors >> Curve Info)
    - "Log to File" under Menu in curve analysis view to export all data for entire trial
    - Use goniometer button to set starting 90-degree angle (90 – 180, so 90 degrees in starting position (anatomical reference))
    - Use the panel control to set the upper and lower limits
    - Set ± 0 degrees to prevent participant movement during the trial
6. Fill out >>Subject Measurements<<
7. Ask participant to transfer from personal wheelchair to treatment table to Biodex chair.
8. A) <u>One researcher</u> will begin to prep and place Delsys Trigno EMG sensors on the participant remembering to clean skin with alcohol and shave hair if needed
    - In Vicon Nexus, change view to Graph and check raw EMG signal for all sensors during placement

   B) <u>One researcher</u> will setup the participant's wheelchair.

- They will affix markers to the subject's wheelchair using the WC_Markers_Placement_Guide and obtain 2 static images of the wheelchair using Vicon. Record file name in >>Motion Capture DCS<<
- They will then affix the SmartWheel (with battery) to the EMG assessment side and the dummy wheel to the non-EMG assessment of the participant's personal wheelchair.
- Next, they will turn on, setup, and sync the SmartWheel laptop with Vicon Nexus by completing the following steps:
    a) Plug in and turn on SmartWheel laptop in the data collection station.
    b) Plug in the custom parallel port adapter into the back of laptop and A/D board pin #7.
    c) Insert the ZyAir dongle into a USB port of the laptop.
    d) Open SmartWheel Software on the laptop desktop.
    e) Turn on the SmartWheel and do not move the wheelchair.
    f) SmartWheel will beep and light will flash when it has connected to the laptop.
    g) Right-click on the OutFront symbol in the bottom right corner of the screen and click Open Research Mode.
    h) In Vicon Nexus, under System >> SmartWheel >> Devices >> #1 SmartWheel [1000 Hz], open Monitors tab, verify Monitors 1&2 exist, and the parameters are correct (see below)
        i. 1. Threshold Mode: Above Upper
        ii. 1. Upper Threshold (V): 0.05
        iii. 1. Condition: On Enter
        iv. 2. Threshold Mode: Below Lower
        v. 2. Lower Threshold (V): 0.05
        vi. 2. Condition: On Enter

9. A) One researcher will move the participant, operate the Biodex, and fill out the >>MMT & MVIC DCS<<
    - Use the >> Biodex MMT & MVIC Protocol<< for participant positioning
    - Follow >>Biodex Instructions<< for additional information

   B) One researcher will operate Vicon Nexus to collect and save MVIC trial data. In Vicon Nexus, change view to Graph and select the desired sensor on the left-hand side to check raw EMG signals for each trial. Record trial notes in >>Motion Capture DCS<<. Save trials in Vicon Nexus in the following location:

    - C:\Vicon Data\R01 WC Lifespan\
        i. Adult_Adult Onset SCI
        ii. Adult_Pediatric Onset SCI
        iii. Child_Pediatric Onset SCI

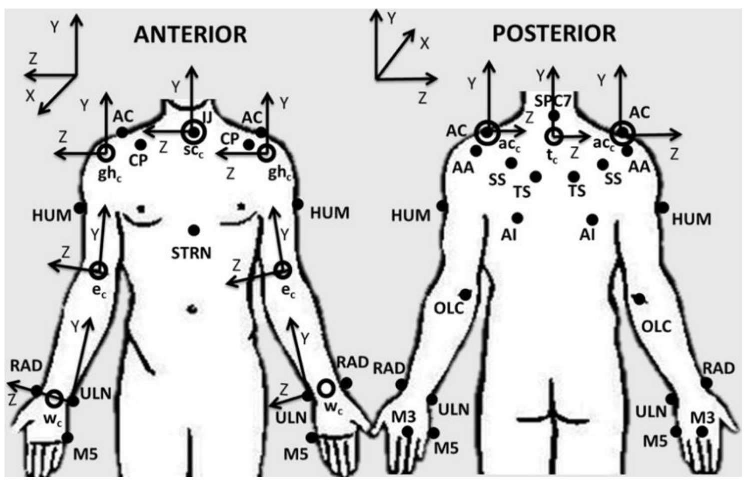
- 0## (Participant ID)

Ex: C:\Vicon Data\R01 WC Lifespan\ Adult_Adult Onset SCI\001

- MVIC_xx_0x
  - iv. xx = AD (anterior deltoid), MD (middle deltoid), PD_ext (posterior deltoid extension), PD_post.hor.add (posterior deltoid posterior horizontal adduction), UT (upper trapezius), BB (biceps brachii), TB (triceps brachii), PM_ant.hor.add (pectoralis major anterior horizontal eadduction), PM_int.rot (pectoralis major internal rotation), or IS (infraspinatus)
  - v. x = trial number

Ex: C:\Vicon Data\R01 WC Lifespan\ Adult_Adult Onset SCI\001\MVIC_AD_01

10. Ask participant to transfer from the Biodex chair to treatment table to personal wheelchair.
11. Affix passive markers to participant and wheelchair and remove unnecessary markers on wheelchiar(see below for markers to keep)
    - Top and bottom four corners of the backrest
    - Wheel axles



12. Using the SmartWheel laptop as the remote trigger, start collecting data (EMG and kinematics) in Vicon
    - In Vicon Nexus under Tools, select the Capture icon, under Auto Capture Setup, and click Arm and the lock symbol to use SmartWheel laptop as the remote trigger to initialize data collection for motion capture trials.
    - On the SmartWheel laptop in the Research Window, click the Enable Trigger Out box.
    - Fill out the >>Motion Capture DCS<< for all motion capture trials
13. Complete Subject Calibration
    - Have the participant seated stationary in their wheelchair facing the data collection station in an anatomical neutral position. Make sure hands are resting on armrest or lap, not handrims.

- Create a new subject with the correct UE Model in Vicon
- Use “Guide to Autolabeling” document to label markers

14. Collect 2-3 static trials (~ 3 seconds each) in Vicon Nexus using the SmartWheel laptop as the remote trigger.
    - Save the trials in Vicon Nexus <u>AND</u> the SmartWheel laptop as Static_0x
      vi. x = trial number
      Ex: C:\Vicon Data\R01 WC Lifespan\ Adult_Adult Onset SCI\001\Static_01

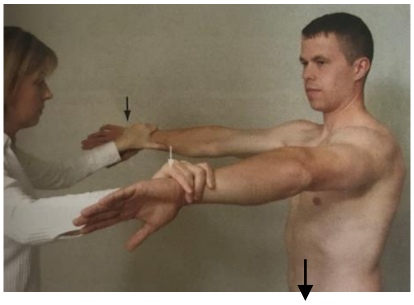
15. Remove the TS and AI markers and have the participant perform function range of motion movements (i.e., elbow flexion/extension, wrist flexion/extension, forearm pronation/supination, and shoulder abduction/adduction). Collect 2-3 trials in Vicon Nexus using the SmartWheel laptop as the remote trigger.
    - Save the trials in Vicon Nexus <u>AND</u> the SmartWheel laptop as Functional_ROM_0x
      vii. x = trial number
      Ex: C:\Vicon Data\R01 WC Lifespan\ Adult_Adult Onset SCI\001\Functional_ROM_01

16. Find area in capture volume where all markers on the participant are first visible to the Vicon cameras and place two starting cones.
17. Find area in capture volume where all markers on the participant are last visible to the Vicon cameras and place two finishing cones.
18. Have the participant propel their wheelchair forward starting from one set of cones and pushing through the other set of cones. Repeat 5x. Allow the participant rest and water breaks as needed.
    - Save the trials in Vicon Nexus <u>AND</u> the SmartWheel laptop as Propulsion_x_xx
      viii. x = side with SmartWheel: R (right) or L (left)
      ix. xx = trial number
      Ex: C:\Vicon Data\R01 WC Lifespan\ Adult_Adult Onset SCI\001\Propulsion_R_01

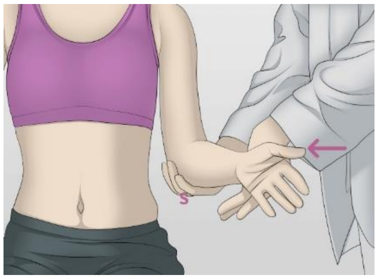
19. Ask the participant to transfer to the treatment table. Flip the SmartWheel and dummy wheel on the wheelchair.
20. Repeat Step 18.
21. Remove all SmartWheels and dummy wheels and replace with participant’s personal wheels.
22. Set up roller system as instructed in <u>>>6MPT Protocol<<</u> and distance sensor as instructed in <u>>>Cycle Computer Setup<<</u> and collect data from this trial on >>Motion Capture DCS<<

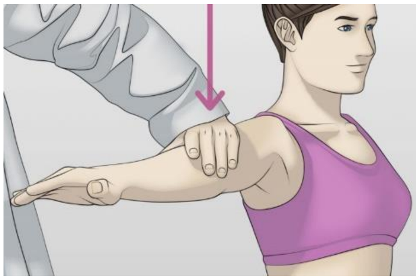
Special Tests - Clinical Exam Guide

Empty Can Test: Shoulder flexion to 90 degrees, shoulder horizontal abduction to 45 degrees (in scapular plane), elbows fully extended, and internal rotation (thumb facing down). Therapist applies resistance to abduction (applies downward force). Positive sign is weakness or pain. This test indicates a tear of the supraspinatus tendon.



Pain/weakness with resisted ER/Abd: The patient attempts to externally rotate the arms against resistance while the arms are at the sides and the elbows flexed to 90 degrees. The patient attempts to abduct the arms against resistance. Positive sign is weakness or pain.

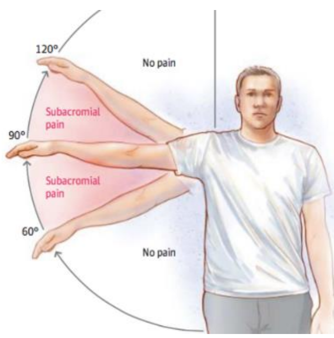




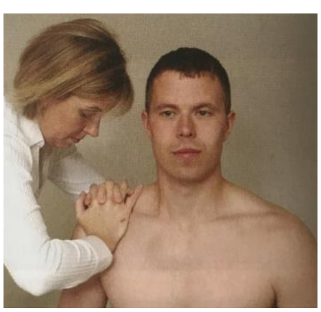
Neer Impingement Sign: Test for impingement of the rotator cuff tendons under the coracoacromial arch. The arm is passively and forcibly fully elevated in the scapular plane with the arm internally rotated. If the patient expresses pain, the sign is positive, indicating compression and/or inflammation of the supraspinatus and/or long head of the biceps.

Hawkins Test: Hawkins' test is for subacromial impingement or rotator cuff tendonitis. Shoulder and elbow are flexed to 90 degrees followed by forced internal rotation and horizontal adduction. If the patient expresses pain, the test is positive, indicating compression and/or inflammation of the supraspinatus and long head of the biceps.

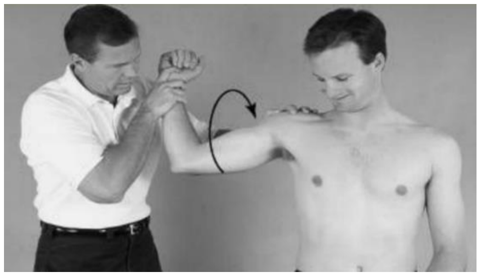
Painful Arc Test: The Painful Arc Test is considered positive for supraspinatus impingement if the patient reports pain between 60 degrees and 120 degrees of abduction. Pain should reduce after 120 degrees of abduction.



AC Joint Compression Test (Shear Test): Clinician should place one hand over the clavicle and one hand on the spine of the scapula, cupping the deltoid muscle. Slowly but firmly press on both sides of the shoulder to compress the AC joint. This compression should be held for a few seconds. A positive test indicating a possible AC joint separation is when extreme pain is elicited in the shoulder during the compression.

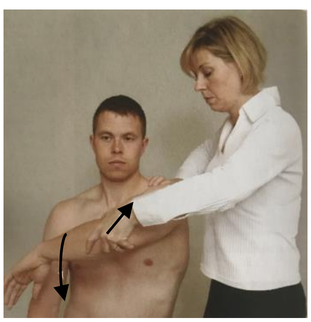


Anterior Apprehension Test: Apprehension test is for anterior instability. The patient's arm is abducted to 90 degrees while the examiner externally rotates the arm and applies anterior pressure to the humerus. (stabilize with second hand anterior to scapula). If positive (patient experiences pain or concern), complete the Relocation test.

Relocation Test (if apprehension is positive): Apply posteriorly directed force over externally rotated humeral head. Positive test is release of apprehension.

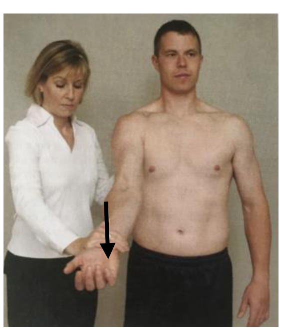
Posterior Apprehension Test: Apprehension test is for posterior instability. The patient's arm is flexed to 90 degrees at the shoulder and elbow and horizontally adducted while the examiner internally rotates the arm and applies posterior pressure to the humerus. (stabilize with second hand posterior to scapula). Positive if patient experiences pain or shows concern.

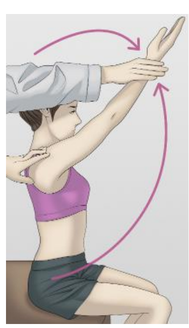


Sulcus Sign Test: Sulcus test is for glenohumeral instability. Downward traction is applied to the humerus, and the examiner watches for a depression lateral or inferior to the acromion.

Gagney Hyperabduction Test: Examiner stands behind the patient with their forearm pushed down against the shoulder girdle using the other hand to gently passively abduct the patient's arm. Abduction over 105 degrees is positive test and reflects increased laxity.

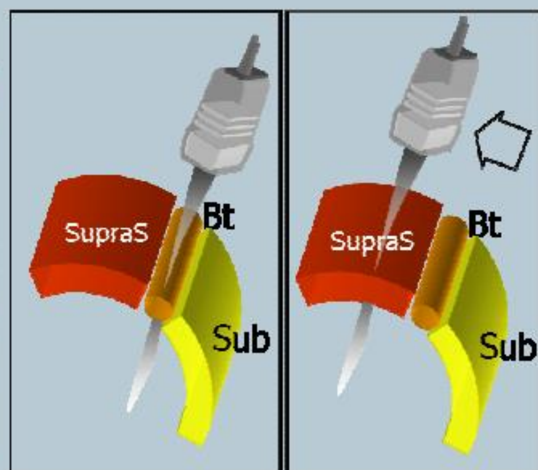
Biceps Speeds Test:
Shoulder flexed to 90 degrees, forearm extended and supinated, and elbow extended. Resistance is applied to flexion (downward force using a long lever arm) while palpating the bicipital groove. Positive sign is pain over bicipital groove, indicating bicipital tendinitis, impingement syndrome, or rotator cuff bursitis

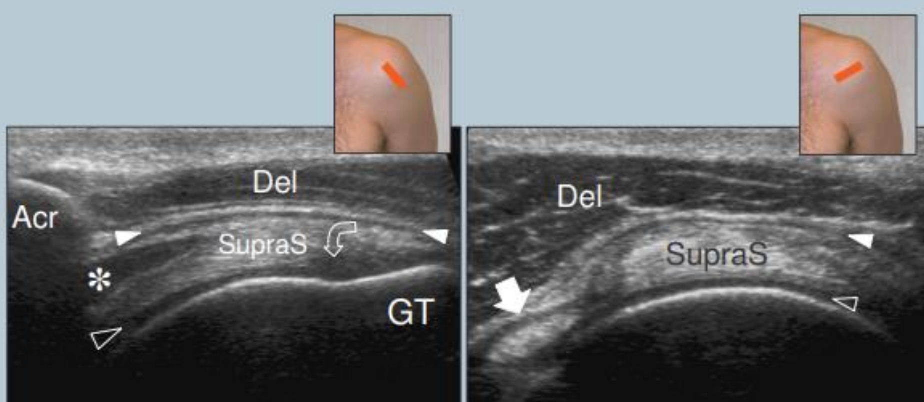




5 supraspinatus tendon

Refer to the intraarticular portion of the biceps as a landmark to obtain proper transducer orientation for imaging the supraspinatus. In fact, these tendons run parallel one to the other and the intraarticular portion of the biceps is easy to be recognized due to a more clearly defined fibrillar pattern. One should rotate the transducer until the biceps is depicted as more elongated as possible in the US image. Then, the probe is shifted upward and posteriorly over the supraspinatus without changing its orientation. The resulting image is in axis with the supraspinatus. Between the supraspinatus and the deltoid, the normal subacromial-subdeltoid bursa appears as a thin hypoechoic band.



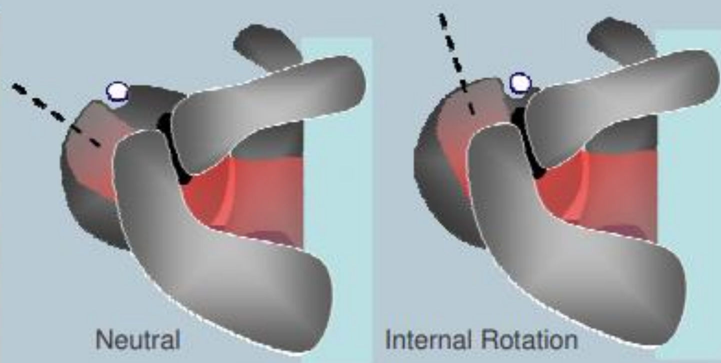


Tilt the transducer gently in the area overlying the tendon insertion to avoid anisotropy. Remember to scan the lateral pouch of the subacromial subdeltoid bursa along the lateral edge of the greater tuberosity. When looking for the supraspinatus on short-axis, the normal cuff must have almost the same thickness from the biceps tendon landmark until 2cm backwards: from this point backwards the tendon seen is the infraspinatus.

Legend: Acr, acromion; asterisk, myotendinous junction; Del, deltoid muscle; GT, greater tuberosity; void arrow-head, articular cartilage; curved arrow, hypoechoic artifact related to anisotropy; straight arrow, long head of the biceps tendon; SupraS, supraspinatus tendon; white arrowhead, subacromial subdeltoid bursa

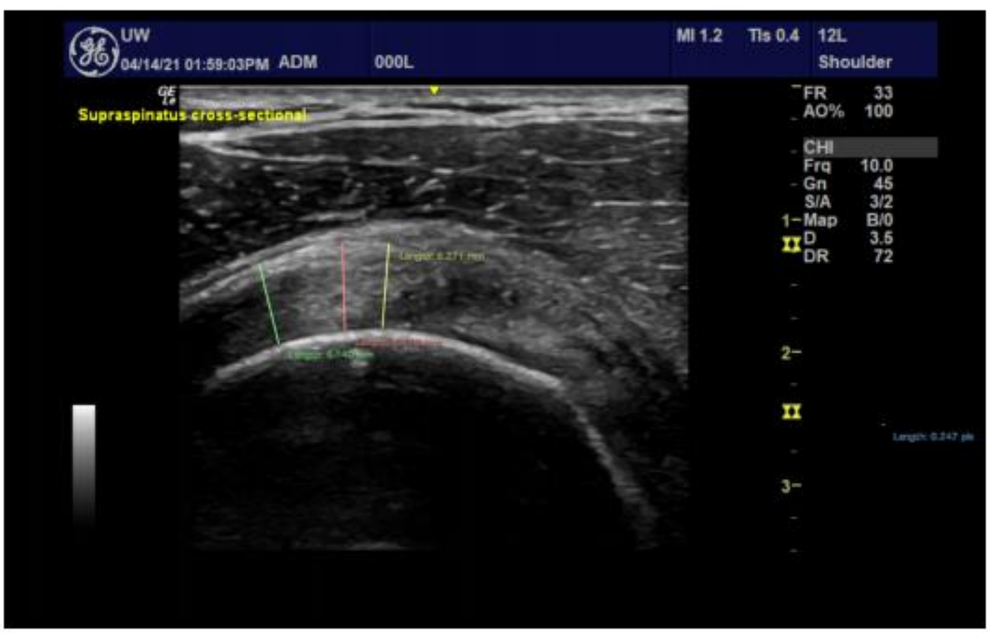
6 supraspinatus tendon: positioning (2)

Place the dorsum of the hand over the opposite back pocket (forced internal rotation, stress manoeuvre). There should not be any space gap between the elbow and the lateral chest wall. Using this position, the supraspinatus becomes a more anterior structure and the transducer should be oriented almost vertically to be in axis with it. Consider that the tendon fibers are more stretched than in the position described at point -5. This may be possible cause of overestimation of tear size. Due to an excessive internal rotation, the long head of the biceps tendon may be difficult to be visualized in this position.



4) Suprasapinatus Tendon Thickness
   000L-9 (Cross-sectional View)

Image should include biceps tendon. The subacromial-subdeltoid bursa should be seen as a single thin hyperechoic line superior to the tendon.



(Longitudinal View)
000L-12

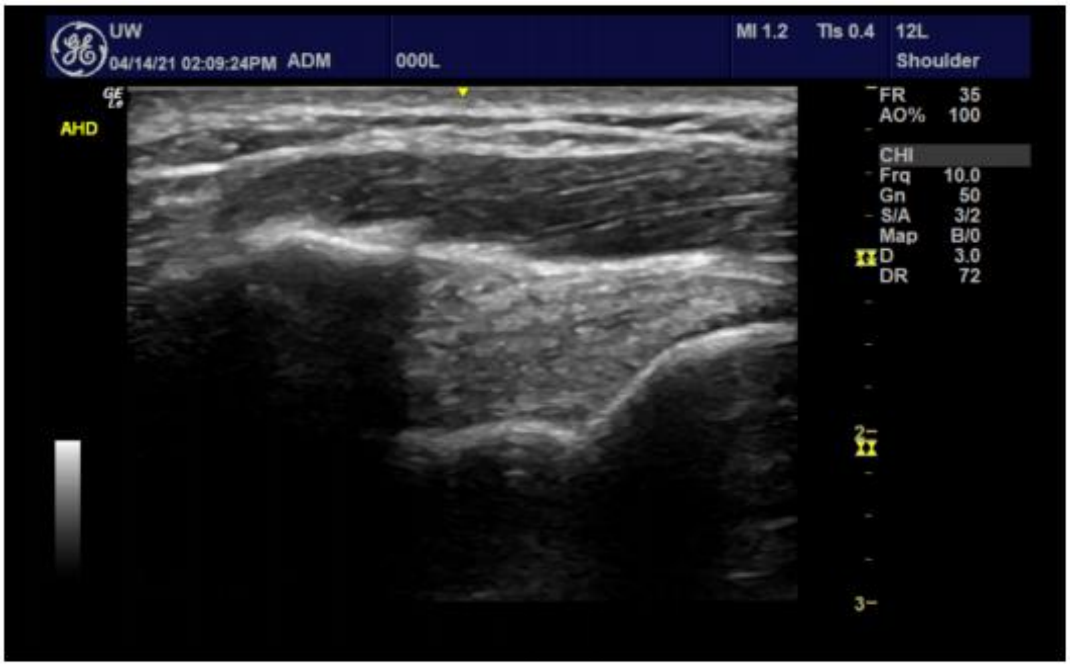
Keep humeral head superior surface parallel with horizontal axis. Should again be able to visualize the subacromial-subdeltoid bursa.

7) Supraspinatus Muscle Cross-Sectional Area
000L-14

Capture thickest portion of the muscle where superior and inferior borders can still be visualized. Should be able to visualize the central tendon as a hyperechoic structure parallel to the superior margin of the muscle. Likely able to visualize entire muscle in pediatric participants.

5) Acromiohumeral Distance
000L-24

Should clearly visualize curvature of lateral border of acromion, along with the margin of humeral head. Supraspinatus tendon thickness will be measured on this image to compute tendon occupation ratio of the subacromial space.



Wheelchair Settings Protocol

A. Take a static image of the participant's wheelchair (their wheels, not Smartwheels) with these 10 markers (shown above) and label it WC_measurement_static:

1. Left axle
2. Right axle
3. Front right seat (top of front right corner of seat cushion)
4. Front left seat
5. Back right seat (top of back right corner of seat cushion where it meets the backrest)
6. Back left seat
7. Top right backrest
8. Top left backrest
9. Front right seat frame (if possible, place a marker towards the front of the right metal frame that the seat cushion rests on – frame should be parallel to the depth of the seat cushion)
10. Back right seat frame (if possible, place a marker towards the back of the right metal frame that the seat cushion rests on – should be parallel to depth of the seat cushion)
11. If the chair has a higher curved back, place markers 7 and 8 at the top of the straight edge before the curve and add an 11th marker to the top center of the backrest (see image below)

**Make sure all 10-11 markers are visible in Vicon – may need to remove armrests if obstructing view of markers

12. Take photos of the wheelchair with markers using camera
13. Remove all wheelchair markers to put SmartWheels on EXCEPT right axle and left axle. These should stay on.

B. Take a static image of the participant (w/ UE markers on) in their wheelchair (w/ L and R axle markers) at top dead center of handrim and label it WC_Subject_static:

1. Make sure that all necessary markers are visible:
    - Make sure that 2 axle markers have been placed on SmartWheels if wheels were swapped
    - Make sure that L/R acromion process, L/R olecranon, L/R humerus, L/R ulnar styloid, L/R medial and lateral epicondyles, and L/R axle markers are visible in Vicon image
        - If the other UE markers are not visible for this image that is OK

2. Instructions for Participant:
    - Instruct participant to "sit as far back in your chair as possible and to sit up as straight as you can"
        - Make sure they are not leaning forward in their chair unless that is their natural posture. If back markers are in the way, have them sit back as is comfortable.
    - Instruct participant to "grab the very top centers of the handrims and tuck your elbows in, so they are in line with the wheels"

3. Check to Make Sure:
    - Subject's forearms are running relatively parallel to the wheels in the sagittal plane.
        - Make sure they are not flaring or bowing their elbows out past the limits of the wheels (see image above)
    - Markers of the 3rd metacarpals are aligned with the top-dead-center of the handrim
        - Directly above the wheel axles, making a perpendicular line with floor (see image above)
4. Take photos of participant in their wheelchair (1 from front, 1 from side) using camera

Appendix F: Wheelchair Equations

Defining Variables

LWHEEL – left axle
RWHEEL – right axle
FRSeat – front right seat
FLSeat – front left seat
BRSeat – back right seat
BLSeat – back left seat
TRBR – top right backrest
TLBR - top left backrest
FRSF – front seat frame
BRSF – back seat frame
TMBR – top middle backrest
ACR – acromion process
OLC – olecranon process
ULN – ulnar styloid

Equation 1: Seat Dump Angle

seatslope=(FRSF(1,3)-BRSF(1,3))./(FRSF(1,2)-BRSF(1,2))
dump angle=atand(seatslope)

Equation 2: Seat to Backrest Angle

x10=TRBR(1,1)-BRSeat(1,1)
y10=TRBR(1,3)-BRSeat(1,3)
x20=FRSeat(1,1)-BRSeat(1,1)
y20=FRSeat(1,3)-BRSeat(1,3)
seattoback=atan2(abs(x10*y20-x20*y10),(x10*y10+x20*y20))
seat to backrest angle=rad2deg(seattoback)

Equation 3: Seat Height

seat height = top of seat – floor
seat height = BRSeat (1,3)

Equation 4: Wheelchair Width

wheelchair width = right axle – left axle
wheelchair width = sqrt(sum((RWHEEL-LWHEEL).^2))

Equation 5: Backrest Height

backrest height = top of backrest – back of seat
backrest height = sqrt(sum((TRBR-BRSeat).^2))

Equation 6: Elbow Angle

elbow = atan2(norm(cross(ACR-OLC, ULN-OLC)),dot(ACR-OLC, ULN-OLC))
elbow angle=rad2deg(elbow)

Appendix G: Matlab Code

Wheelchair Measurements (Seat Angle)

```
data=csvread('C:\Users\hanna\OneDrive - UWM\Thesis\WC_Static_01.csv',6,0)
LWHEEL=mean(data(1:200,3:5))
RWHEEL=mean(data(1:200,6:8))
wheelchairwidth=sqrt(sum((RWHEEL-LWHEEL).^2))
%distance between 2 points

BRSeat=mean(data(1:200,15:17))
seatheight=BRSeat(1,3)
%z position

FRSF=mean(data(1:200,30:32))
BRSF=mean(data(1:200,33:35))
seatslope=(FRSF(1,3)-BRSF(1,3))./(FRSF(1,1)-BRSF(1,1))
%this is the slope in the z/x direction)
dumpangle=atand(seatslope)

FRSeat=mean(data(1:200,9:11))
TRBR=mean(data(1:200,21:23))
x10=TRBR(1,1)-BRSeat(1,1)
y10=TRBR(1,3)-BRSeat(1,3)
x20=FRSeat(1,1)-BRSeat(1,1)
y20=FRSeat(1,3)-BRSeat(1,3)
seattoback=atan2(abs(x10*y20-x20*y10),(x10*y10+x20*y20))
seattobackangle=rad2deg(seattoback)
%in the sagittal plane (x/z coordinates) and BRSeat is the middle point of
%the angle
backrestheight=sqrt(sum((TRBR-BRSeat).^2))
%distance between 2 points

TMBRz=mean(data(1:200,29))
BRSeatz=mean(data(1:200,17))
altbackrestheight=TMBRz-BRSeatz
```

Subject Measurements (Elbow Flexion Angle)

```
data=csvread('C:\Users\hanna\OneDrive - UWM\Thesis\Subj_102_01.csv',6,0)
RACR=mean(data(1:600,21:23))
RLATEP=mean(data(1:600,15:17))
RHUM=mean(data(1:600,18:20))
RULN=mean(data(1:600,3:5))
Relbow=atan2(norm(cross(RACR-ROLC,RULN-ROLC)),dot(RACR-ROLC,RULN-ROLC))
Relbowangle=rad2deg(Relbow)

LACR=mean(data(1:600,63:65))
LLATEP=mean(data(1:600,60:62))
LHUM=mean(data(1:600,66:68))
LULN=mean(data(1:600,48:50))
Lelbow=atan2(norm(cross(LACR-LOLC,LULN-LOLC)),dot(LACR-LOLC,LULN-LOLC))
Lelbowangle=rad2deg(Lelbow)
```

```
shoulderwidth=sqrt(sum((RACR-LACR).^2))
%distance between 2 points
```

<u>Horizontal Axle Position</u>

```
data=dlmread('101_Propulsion_R_06.csv',",",[17773 0 17927 115]); %[csv row
%that matches the vicon Start Frame from Processing Log/ 0 / csv row that
%matches the Vicon End Frame from Processing log -1/ 115 number of columns]
% -----------------
%LAXLEdata=data(:,18); %Column 18 = LAXLE data column
%LACRdata=data(:,54); %Column 54 = LACR data column
RAXLEdata=data(:,15); %Column 15 = RAXLE data column
RACRdata=data(:,36); %Column 36 = RACR data column
% -----------------
DisplacementX=RAXLEdata-RACRdata; %Takes the difference between the RAXLE
%and RACR data in the X direction. These are the y-values on the graph.
Frame=data(1:155,1); %Sets the length to the number of frames. These are
%x-axis values on the graph.
% -----------------
plot(Frame,DisplacementX); %Plots the Displacement vs. Frame
xline(514); %Start Frame from Processing Log + Contact Start from R01_###_
            %Propulsion_#_##

xline(575);%Start Frame from Processing Log + Contact Start from R01_###_
            %Propulsion_#_## - 1

xline(576);%Start Frame from Processing Log + Contact Start from R01_###_
            %Propulsion_#_##

xline(638);%Start Frame from Processing Log + Contact Start from R01_###_
            %Propulsion_#_## - 1

%xline(748);%Start Frame from Processing Log + Contact Start from R01_###_
            %Propulsion_#_##

%xline(839);%Start Frame from Processing Log + Contact Start from R01_###_
            %Propulsion_#_## - 1
%xline(595);
%xline(654);
% -----------------
MaxCycle1=min(DisplacementX(14:75));%stroke tab for each cycle
MaxCycle2=min(DisplacementX(76:138));
%MaxCycle3=min(DisplacementX(193:284));
%MaxCycle4=max(DisplacementX(180:240));
%MaxCycle4=max(DisplacementX(___:___));
% -----------------

Trial='100_L_05';
TrialPeaks=table(Trial, MaxCycle1, MaxCycle2);
writetable(TrialPeaks,'TrialPeaks.xls','Sheet',1,'Range','A1:E2')

%writematrix(MaxCycle1,'CyclePeaks.xls','Sheet',1,'Range','B2');
%writematrix(MaxCycle2,'CyclePeaks.xls','Sheet',1,'Range','C2');
%writematrix(MaxCycle3,'CyclePeaks.xls','Sheet',1,'Range','D2');
```

Appendix H: Publications

Howard H. Steele Assembly Pediatric Spinal Cord and Dysfunction 2021 Conference

Matthew M. Hanks[1], Hannah R. Frank[1], Alyssa J. Schnorenberg[1], Shubhra Mukherjee[2], Kathy Zebracki[2], Lawrence C. Vogel[2], Brooke A. Slavens[1]

[1]University of Wisconsin-Milwaukee, [2]Shriners Hospitals for Children-Chicago

Title: Manual Wheelchair Setup and Pain in Individuals with Pediatric-Onset Spinal Cord Injury

Objective: To characterize wheelchair setup and pain in manual wheelchair users with pediatric-onset spinal cord injury (SCI).

Methods: Five individuals (3 females, 2 males (mean ± 1SD) age: 13.0 ± 6.2 years, time since injury: 6.2 ± 2.6 years) with pediatric-onset paraplegia (T3-T10 AIS A) participated in this prospective, mixed-methods experimental study. Motion analysis captured positions of markers affixed to the participant's wheelchair and upper extremities while they were seated with their hands positioned at top dead center of the wheel during a single trial. The mean values of the group were computed for the wheelchair sagittal seat angle (angle between the front and back of the seat frame relative to horizontal) and the elbow angle for each arm (angle between the vectors directed from the olecranon process to the acromion process and to the ulnar styloid). Pain was assessed using the Patient-Reported Outcomes Measurement Information System (PROMIS) Pain Interference Short Form (Pediatric v.2.0 or Adult v.1.1) and the Wheelchair User's Shoulder Pain Index (WUSPI) [1,2].

Results: Group mean sagittal seat angle was 4.5 ± 1.8°, right elbow angle was 100.0 ± 11.5°, and left elbow angle was 94.4 ± 12.7°. PROMIS pain interference score was 42.6 ± 8.3, with scores less than 50 representing lower pain interference [3]. The WUSPI score (range: 0-150) was 0.8 ± 1.8, indicating no shoulder pain interference.
Conclusion: In adults, sagittal seat angles less than 10° and elbow angles less than 100° or greater than 120° are associated with pain and pathology [4,5]. The participants had values at or within these ranges; however, they reported low to no pain interference. Wheelchair setup for youths with pediatric-onset SCI appears to be different than current recommendations for individuals with adult-onset SCI. Identifying optimal wheelchair setup could help prevent pain and pathology development across the lifespan.
Learning Objective: To understand the importance of wheelchair setup in manual wheelchair users with pediatric-onset SCI.

Bibliography:

1. Askew, R. L., Cook, K. F., Revicki, D. A., Cella, D., & Amtmann, D. (2016). Clinical Validity of PROMIS® Pain Interference and Pain Behavior in Diverse Clinical Populations. *Journal of Clinical Epidemiology, 73*, 103.

2. Curtis, K., Roach, K., Applegate, E., Amar, T., Benbow, C., Genecco, T., & Gualano, J. (1995). Reliability and Validity of the Wheelchair User's Shoulder Pain Index (WUSPI). *Spinal Cord, 33*(10), 595-601.
3. https://www.healthmeasures.net/score-and-interpret/interpret-scores/promis
4. Giner-Pascual, M., Alcanyis-Alberola, M., González, L. M., Aguilar-Rodríguez, M., & Querol, F. (2011). Shoulder Pain in Cases of Spinal Injury: Influence of the Position of the Wheelchair Seat. *International Journal of Rehabilitation Research*, 34(4), 282-289.
5. Paralyzed Veterans of America Consortium for Spinal Cord Medicine. (2005). Preservation of Upper Limb Function following Spinal Cord Injury: A Clinical Practice Guideline for Health-Care Professionals. *The Journal of Spinal Cord Medicine*, *28*(5), 434.

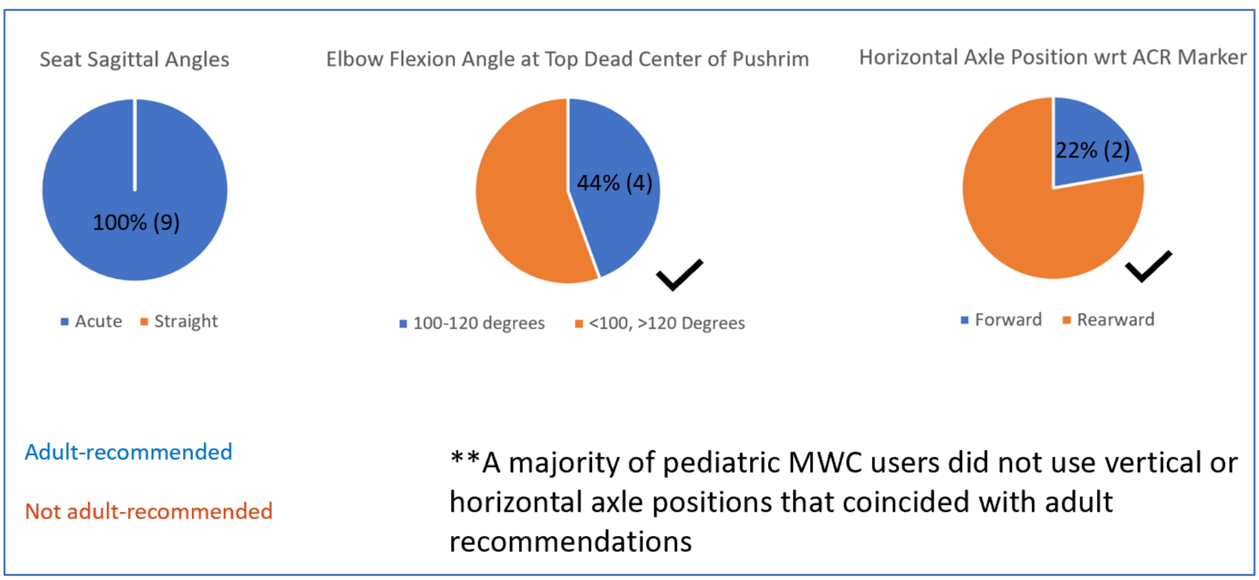
Appendix I: Defense Presentation Additional Figures

1 – Table showing the pediatric subjects whose wheelchair parameters followed adult recommendations

Subject	Seat Sagittal Angle (degrees)	Average ACR X Position wrt to Axle for All Cycles (mm)	Elbow Flexion Angle on Dominant Side at Top Dead Center (degrees)
1	2.58	107.81	106
2	7.2	161.8	103.45
3	5.26	-17.51	79.54
4	3.95	63.55	100.06
5	3.56	77.88	106.24
6	6.32	-35.49	84.23
7	6.18	37.18	95.03
8	4.27	157.68	126.51
9	7.15	74.67	97.04
Average	5.16	69.73	99.79

Smaller elbow angles may signify axles that are too high or seats that are too low

2 – Circle graphs showing the percentage of pediatric subjects whose wheelchair parameters followed adult clinical guidelines



3 – Table showing the relationship between the peditric subjects' age/time since injury and seat angles

Relationship Between Age/Time Since Injury & Seat Angle

		Average Age (yrs)	Average Time Since Injury (yrs)
Seat Angle	<5 degrees	14.91 +/- 4.3	8.48 +/- 4.13
	>5 degrees	15.32 +/- 7.74	12.04 +/- 6.48
Horizontal Axle Position	Rearward	15.5 +/- 5.41	10.26 +/- 4.67
	Forward	13.87 +/- 10.74	11.16 +/- 10.72
Elbow Flexion Angle	<100, >120 degrees	16.6 +/- 2.93	13.32 +/- 2.62
	100-120 degrees	13.3 +/- 2.87	6.88 +/- 1.21

**Individuals with larger seat angles were more likely to have had their injury for longer

**May indicate that new users keep standard, straighter seat angles until they build more confidence with transfers and then prioritize comfort

4 – Table showing the relationship between the pediatric subjects' age/time since injury and seat angles

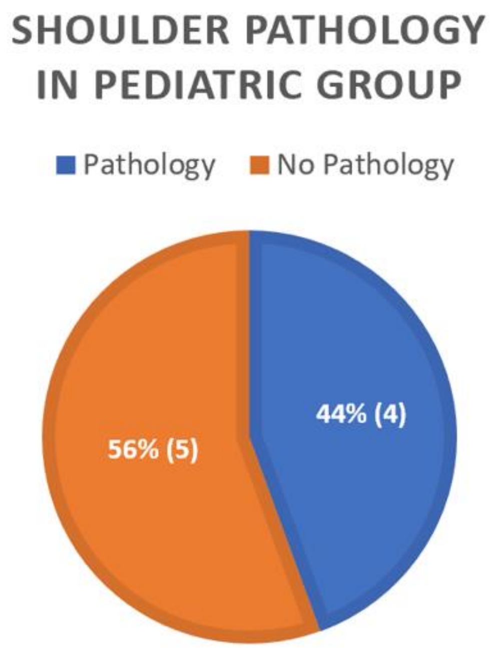
Relationship Between Age/Time Since Injury & Horizontal Axle Position

Subject	Age (years)	Time since Injury (years)	Level of Injury	Seat Sagittal/Dump Angle (degrees)	Elbow Angle (degrees)	ACR X Position wrt to Axle (mm)
100	13.93	10.23	T10	2.58	106.00	107.81
101	7.48	7.10	T6	7.20	103.45	161.80
102	6.27	3.58	T6	5.26	79.54	-17.51
103	10.82	5.28	T4 C	3.95	100.06	63.55
104	20.97	4.93	T5/T6	3.56	106.24	77.88
105	21.46	18.74	L3	6.32	84.23	-35.49
106	21.28	16.92	T1	6.18	95.03	37.18
107	13.90	13.50	L3	4.27	126.51	157.68
108	20.11	13.87	T7	7.15	97.04	74.67

**Interestingly, the youngest participant and the oldest participant were the only two to use a forward axle position, but they also had the smallest elbow flexion angles

**May indicate that a more forward axle position can compromise the elbow flexion angle

5 – Graph showing the percentage of pediatric subjects who have shoulder pathologies



6 – Table showing the relationship between pediatric subjects' wheelchair settings and their supraspinatus tendon thicknesses

Relationship Between Wheelchair Settings & Supraspinatus Tendon Thickness

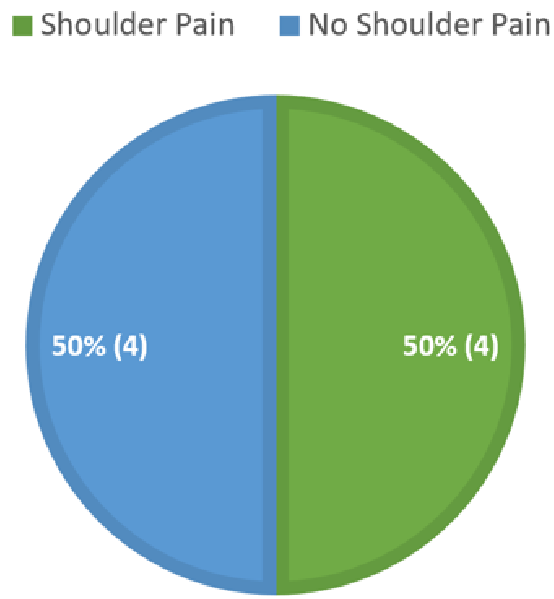
	Average Supraspinatus Tendon Thickness - Both (cm)
Rearward Axle Position	0.60 +/- 0.17
Forward Axle Position	0.55 +/- 0.09

	Average Supraspinatus Tendon Thickness - Both (cm)
< 5 degrees	0.66 +/- 0.2
> 5 degrees	0.54 +/- 0.09

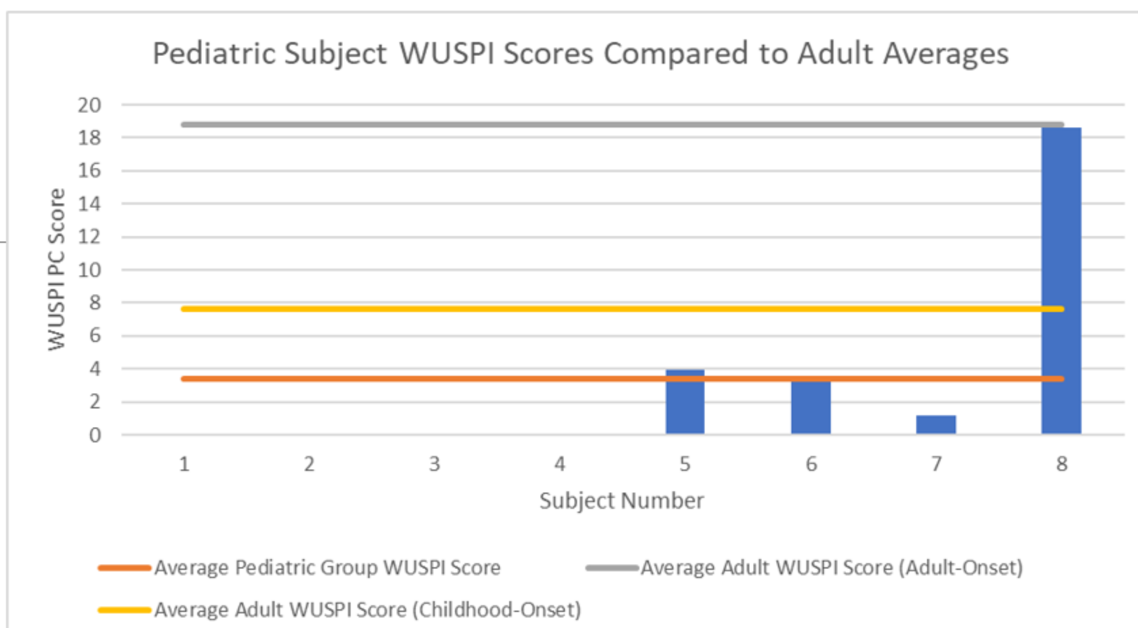
**As was hypothesized, individuals with straighter seat angles and more rearward axle positions had larger supraspinatus tendon thicknesses

**May indicate that these are detrimental positions for pediatric MWC users as well and may lead to inflammation/subacromial impingement

7 – Graph showing the percentage of pediatric subjects who reported shoulder pain



8 – Graph showing the pediatric subjects' WUSPI scores compared to previously recorded adult averages for adult-onset SCI and pediatric-onset SCI groups



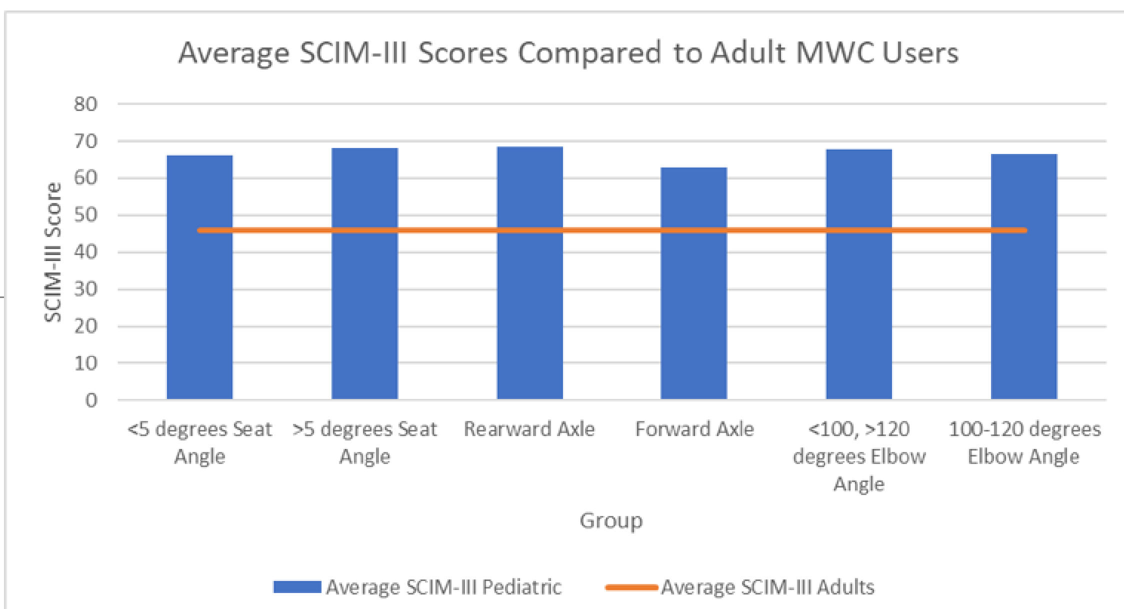
9 – Table showing the average WUSPI scores for pediatric subjects based on their wheelchair parameters

		Average WUSPI PC Score	Standard Deviation
Seat Angle	<5 degrees	5.637	8.848
	>5 degrees	1.17	1.64
Horizontal Axle Position	Rearward	3.96	7.34
	Forward	1.73	2.45
Elbow Flexion Angle	<100, >120 degrees	5.82	4.33
	100-120 degrees	0.98	0.98

**As was hypothesized, straighter seat angles, more rearward axles, and "non-optimal" elbow flexion angles were associated with higher pain severity scores

** May indicate that these are more dangerous/detrimental wheelchair settings that could lead to pain in pediatric MWC users with SCI

10 – Graph showing the average SCIM scores for pediatric subjects based on their wheelchair parameters compared to previously reported average SCIM scores for adult wheelchair users



11 – Table showing the average SCIM scores for pediatric subjects based on their wheelchair parameters

		Average SCIM-III Score	Standard Deviation
Seat Angle	<5 degrees	66.25	4.787
	>5 degrees	68	10.68
Horizontal Axle Position	Rearward	68.5	2.08
	Forward	63	11
Elbow Flexion Angle	<100, >120 degrees	67.75	10.53
	100-120 degrees	66.5	5.2