THE IMPACT OF A PUSHRIM ACTIVATED POWER ASSIST WHEELCHAIR AMONG INDIVIDUALS WITH TETRAPLEGIA

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The goal of this project was to test the influence of a pushrim activated power-assisted wheelchair (PAPAW) on the functional capabilities of individuals with cervical level spinal cord injuries (tetraplegia). This repeated measures design type study was divided into two phases, which included testing in two different laboratory settings: a biomechanics laboratory and an activities of daily living laboratory. Fifteen participants included in both phases were fulltime manual wheelchair users (MWUs) with tetraplegia.

The purpose of the first phase of the study was to determine the differences in metabolic demands, stroke frequency, and upper extremity joint range of motion, during PAPAW propulsion and traditional manual wheelchair propulsion. Participants propelled both their own manual wheelchairs and a PAPAW through three different resistances (slight, moderate and high), on a computer controlled wheelchair dynamometer. Variables analyzed during this phase included: mean steady state oxygen consumption, ventilation, heart rate, mean stroke frequency, maximum upper extremity joint range of motion, and propulsion speed. Results from the first phase of the study revealed a significant improvement in kinematic, speed, and metabolic variables when participants were propelling with a PAPAW.

In Phase II, participants propelled both their own manual wheelchairs and a PAPAW three times over an activities of daily living course. The course was constructed to reflect

certain obstacles that a manual wheelchair user might encounter in his or her daily routine. PAPAWs received higher user ratings than the participant's own manual wheelchair for 10 out of 18 obstacles. Additionally, when using a PAPAW, participants were able to complete the course in the same amount of time while maintaining a lower mean heart rate.

For individuals with tetraplegia, PAPAWs have the potential to decrease metabolic demands during propulsion, while increasing or maintaining function within ADLs. Use of this device could help MWUs maintain overall physical capacity while reducing the risk for pain and injuries to the upper extremities, which are often seen among manual wheelchair users with tetraplegia. Future studies with this device should focus on the ability of MWUs with tetraplegia to perform necessary activities of daily living within their home environment and community.

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1.0 INTRODUCTION

For the estimated 2.2 million people in the United States who use them, manual wheelchairs offer those with disabilities the means to maintain independence within their home, workplace, and community.[1] And though the manual wheelchair's impact on the lives of people with disabilities cannot be understated, there are numerous drawbacks to manual wheelchair propulsion. The upper extremity serves as the main means of propulsion for the wheelchair user, and was not developed for this sort of function. As a result, full time manual wheelchair users (MWUs) often experience shoulder, elbow and wrist pain and injuries.

Furthermore, MWUs with impaired upper extremities, such as individuals with cervical level spinal cord injuries (tetraplegia), are at even more at risk for developing repetitive strain injuries and pain. This can be attributed to a combination of factors, including: reduced overall physical capacity and upper extremity muscle weakness. In addition, environments and community settings are not often designed for individuals with disabilities in mind. As a result, MWUs often have to put their bodies into unnatural positions, where they increase the likelihood for developing injuries to their upper extremities. For example, people who use wheelchairs often have to reach up for objects, placing their shoulder joint into extreme abduction. Though one's home environment can be accommodated to maximize task completion and accessibility, MWUs who are active in the community cannot always control the outside environmental obstacles they encounter. Similarly, though training and conditioning can affect an individual's physical capacity and the ability to complete ADLs, there are mitigating factors (e.g. the level of injury, a predisposition to upper limb injury, and age-related changes in the musculoskeletal system) that cannot be controlled. What can be controlled, at practically all times, is the assistive technology device and how much effort is demanded of the individual to maintain function when using the device.

Alternative devices to manual wheelchairs are often used to meet the mobility needs of people with disabilities. In the past, these have typically included power wheelchairs and powered scooters. Powered scooters are not often a feasible substitute to manual wheelchairs due to their inability to provide the proper body positioning and support that the user may need. Furthermore, due to increased size and weight, powered scooters are not as easy to transport as manual wheelchairs. Although powered wheelchairs can provide sufficient positioning and support, they are also difficult to transport due to the increased weight. Alternative methods of manual wheelchair propulsion, such as lever-drive units, arm cranks, and geared hubs, have also been developed. Although these devices increase the user's mechanical efficiency, they are more functional outdoors and are not typically used for an individual's total mobility needs.

The recent developments of Pushrim Activated Power Assisted Wheelchairs (PAPAWs) have provided MWUs with an appealing mobility device alternative. These are manual wheelchairs with a power-assisted hub, where the unit automatically supplements the user's manual pushrim input with additional rear-wheel torque. These devices have the potential to significantly reduce the effort and strain that MWUs typically put on their upper extremities, while providing the transportability of manual wheelchairs. The work presented in this thesis contains the first two of three phases in an on-going study to determine the impact of PAPAWs on the mobility of MWUs with tetraplegia.

(1) USCensus. (2002). Disability [web page]. US Census Bureau. Retrieved September 26, 2002, from the World Wide Web: http://www.census.gov/hhes/www/disability.html

2.0 PHASE I: IMPACT OF A PUSHRIM ACTIVATED POWER ASSIST WHEELCHAIR ON THE METABOLIC DEMANDS, STROKE FREQUENCY AND RANGE OF MOTION AMONG INDIVIDUALS WITH TETRAPLEGIA

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2.1 ABSTRACT

The purpose of this study was to determine the differences in metabolic demands, stroke frequency, and upper extremity joint range of motion, during pushrim activated power-assisted wheelchair (PAPAW) propulsion and traditional manual wheelchair propulsion among individuals with tetraplegia. It was a repeated measures design study and was conducted in a biomechanics laboratory within a Veterans Affairs medical center. Fifteen fulltime manual wheelchair users with tetraplegia participated in the study.

Participants propelled both their own manual wheelchairs and a PAPAW through three different resistances (slight, moderate and high), on a computer controlled wheelchair dynamometer. For metabolic testing, the variables that were compared between the two wheelchairs were the participants' mean steady state oxygen consumption, ventilation, and heart rate. For kinematic testing, the variables compared were mean stroke frequency, in addition to maximum upper extremity joint range of motion for: shoulder flexion/extension, internal/external rotation, abduction/adduction, horizontal flexion/extension; wrist flexion/extension, pronation/supination, ulnar/radial deviation; and elbow flexion/extension.

When using the PAPAW, participants showed a significant ($p < 0.05$) decrease in mean oxygen consumption and ventilation throughout all trials. Mean heart rate was not significantly different between the two wheelchairs for the slight and moderate resistances, but was significantly lower when using the PAPAW for the high resistance trial. Conversely, stroke frequency was significantly lower when using the PAPAW for the slight and moderate resistances, but not significantly different at the high resistance. For a majority of the resistance conditions, overall joint range of motion was significantly lower when using the PAPAW for the following motions: shoulder flexion/extension, internal/external rotation, horizontal

flexion/extension; wrist flexion/extension, pronation/supination, ulnar/radial deviation; and elbow flexion/extension.

For individuals with tetraplegia, PAPAWs reduce the energy demands, stroke frequency, and overall joint range of motion when compared to traditional manual wheelchair propulsion. Use of this device could help maintain overall physical capacity while reducing the risk for pain and injuries to the upper extremities, which are often seen among manual wheelchair users with tetraplegia.

2.2 INTRODUCTION

For people with disabilities, manual wheelchair propulsion is commonly an inefficient means of mobility.[1] Furthermore, individuals with cervical-level spinal cord injuries (tetraplegia) may find manual wheelchair propulsion even more difficult because of upper extremity muscle weakness. If combined with upper extremity pain, an individual with tetraplegia could quickly lose their ability to independently propel a manual wheelchair, which could lead to the loss of independent mobility and decreased activity.

It is well documented that upper extremity pain and injuries are prevalent among manual wheelchair users (MWUs).[2-7] The upper extremities were not developed for manual wheelchair propulsion, and these individuals often experience shoulder, elbow and wrist pain and injuries. In fact, the incidence of shoulder pain has been reported to be as high as 73% among MWUs.[6] In a survey study of 77 people with paraplegia, Gellman *et. al.* noted that 49% showed signs and symptoms of carpal tunnel syndrome, and further noted that the prevalence of carpal tunnel syndrome increased with length of time after injury.[8]

The kinematic characteristics of manual wheelchair propulsion have been investigated extensively.[9-17] Many researchers agree that propelling with a high cadence and excessive range of motion of the joints can lead to upper extremity pain and cumulative trauma disorders.[18,19] Koontz *et. al.*, when testing twenty-seven individuals with paraplegia, observed higher peak joint forces in positions where the shoulder was at maximum flexion in the sagittal plane and minimal abduction.[20] When comparing the effects of the level of spinal cord injury on shoulder joint kinematics, Kulig *et. al.* suggested that MWUs with tetraplegia have an increased likelihood of compressing subacromial structures due to high push force combined with weakness of thoraco-humeral depressors.[21] Thus, individuals with tetraplegia may be even more susceptible to pain and injuries of the shoulder joint, and avoiding positions where the shoulder is excessively flexed becomes even more important.

Alternative methods of wheelchair propulsion, such as lever-drive units, arm cranks, and geared hubs, have been developed. For the most part, these have fallen short in presenting feasible and commercially appealing solutions.[22,23] Pushrim Activated Power Assist Wheelchairs (PAPAWs) offer an alternative between manual wheelchairs, lever-drive systems, and powered mobility devices. These are typically manual wheelchairs with a motor linked to the pushrim in each rear hub, where the user's manual pushrim input is supplemented proportionally by the motor. Figure 1 shows a schematic diagram of the PAPAW used in this study.

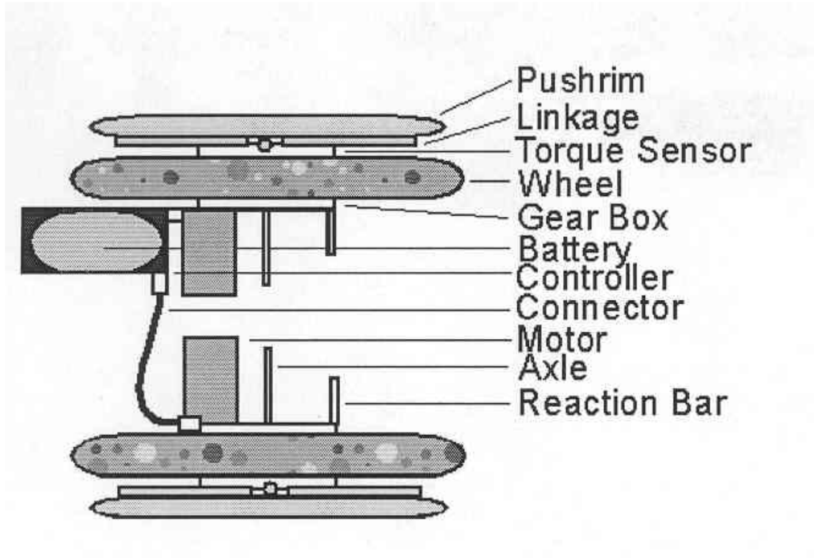

Figure 1. Schematic of PAPAW used in this study.

Studies have shown PAPAWs to have a significant improvement of the mechanical efficiency, joint range of motion, and metabolic demands of the individuals that were tested.[24-27] However, participants included in previous studies have been limited to either MWUs with thoracic level spinal cord injuries (paraplegia), multiple sclerosis, or no disability. No study to date has been conducted that focuses on MWUs with tetraplegia, a population who could significantly benefit from PAPAWs.

The purpose of this study was to compare certain characteristics of pushrim activated power assisted wheelchair propulsion and traditional manual wheelchair propulsion for MWUs with tetraplegia, including the differences in: energy expended, stroke frequency, and upper extremity joint range of motion.

2.3 METHODS

2.3.1 Subject Recruitment

Participants were recruited through the Human Engineering Research Laboratories' registry. They were initially contacted by either letter or telephone. In order to meet the inclusion criteria, participants had to be: between the ages of 18 and 65, full-time manual wheelchair users for at least one year with tetraplegia, free from pressure sores and shoulder pain, and have no reported history of cardiopulmonary disease. Shoulder pain was defined as pain in the shoulders that was currently preventing the participants from propelling their wheelchair or performing their daily activities.

2.3.2 Experimental Protocol

Participants were asked to abstain from eating for two hours prior to testing. For all testing, participants propelled both their own manual wheelchair and a PAPAW in random order on a computer-controlled wheelchair dynamometer.[28] The experimental setup was similar to that described by Shimada *et. al.*[15] Participants were asked to maintain a speed of 0.9 meters per second through three different dynamometer resistance conditions (slight, moderate, and high) for both the PAPAW and their own manual wheelchair. The order of the chairs and resistances were randomized. The resistance conditions simulated trials of propelling on a flat tiled floor (slight: 0.9m/s, 10 Watts), a flat carpet (moderate: 0.9m/s, 12W) and uphill (high: 0.9m/s, 14W).[28] Each of the six propulsion trials was three minutes in length with data collected for the final 30 seconds of the last minute. Participants were provided with five minutes to get acclimated to the test setup, and were provided with a five minute rest between each trial. They were also provided with a visual display of their real time speed throughout the propulsion trials.

The PAPAW available for this study was a Yamaha JWII[a] mounted to a Quickie 2[b] folding frame manual wheelchair, which was selected and adjusted to best match their own wheelchair's current seat dimensions (seat width, seat depth, backrest height, seat to footplate length, pushrim diameter, rear wheel diameter, and axle position). Figure 2 shows a photograph of the PAPAW used for this study.

Figure 2. PAPAW used for testing in this study.

2.3.3 Metabolic Data Collection

Four minutes of physiologic data were collected for each trial: one minute resting, three minutes of propulsion. Each individual's steady state rate of oxygen consumption (VO_2mL/kg x min, VO_2mL/min) and ventilation rate (V_EL/min) were acquired using an Aerograph VO2000 Metabolic Cart,[c] which was calibrated prior to each testing session. This system collects inhaled and expired gases from the participant via a mouthpiece and tube at a sampling rate of 150 Hz. The participant's nose was pinched with a nose-clamp to prevent air loss from the system. Heart rate data were collected using a Polar T31[d] wireless heart rate monitor and was continuously monitored throughout testing, as well as monitored for fifteen minutes upon completion of the testing.

2.3.4 Kinematic Data Collection

Two OPTOTRAK 3D 3020[e] motion analysis cameras were used to collect the position data of infrared markers (IRED) placed on both sides of the participant's body. The location of the markers included the: temporomandibular joint, acromion process, lateral epicondyle, radial styloid, third metacarpophalangeal (MP) joint, fifth MP joint, ulnar styloid, olecranon and three markers for the trunk. Figure 3 provides a visual description of the marker placement.

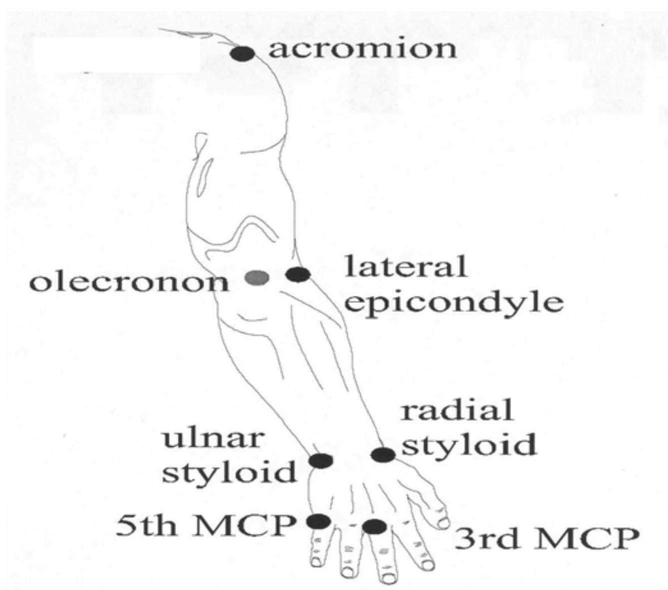

Figure 3. Location of LED markers used during the kinematic testing.

When transferring between the two wheelchairs, the markers were undisturbed. Markers were also placed on both sides of the wheelchair's rear axle. Kinematic data were collected at a 60 Hz frequency and filtered with an eighth-order, zero-phase digital Butterworth filter. Two seated set positions, where the participants held their arms in full adduction, with the elbows flexed to 90 degrees, forearms at zero degrees in pronation/supination, and wrists at zero degrees ulnar/radial deviation, were also recorded with the OPTOTRAK prior to the start of each wheelchair testing. The set position was taken to ensure similar wheelchair setup between the participants' own manual wheelchairs and the PAPAWs.

2.3.5 Statistical Analysis

For the physiological, heart rate, and kinematic data, the last thirty seconds of each trial were analyzed for statistical purposes. Steady state of the participant was confirmed by observing that metabolic and heart rate values reached a plateau after two and a half minutes. Descriptive statistics were performed for all variables, and histograms were evaluated for normal distributions. Paired sample t-tests ($p < 0.05$) were used to compare the means of data that was normally distributed, and Wilcoxon Rank Sum tests were performed on data that were not normally distributed. In addition, a mixed model analysis of variance (ANOVA) was used to determine if differences existed between the two types of chairs and the three resistance conditions. A mixed model was used since it allows for comparison between the two wheelchairs even though the same participant performed the testing of the wheelchairs. Statistical analysis was performed using both SPSS[f] and SAS software.[g] Computational methods and calculations were carried out using MatLab.[h] For stroke frequency and range of motion, the first ten successive strokes were averaged for the variables during each trial. ROM angles were calculated using the methods described in Boninger *et. al.*,[30] Cooper *et. al.*,[31] and Shimada *et. al.*.[32] These included: wrist flexion/extension, ulnar/radial deviation, forearm supination/pronation; elbow flexion/extension; shoulder flexion/extension, abduction/adduction, internal/external rotation, and horizontal flexion/extension.

2.4 RESULTS

2.4.1 Participants

This study received prior approval by the appropriate human studies institutional review boards. Each participant was provided with information about the safety and intent of the tests, and signed informed consent was obtained prior to any testing. Fifteen full-time manual wheelchair users (MUWs) with tetraplegia (cervical level spinal cord injury) participated in the testing. The demographics included: 12 males and 3 females, age 27 to 52 years (mean 37.3, SD 7.3), height 152 to 193 centimeters (mean 180.0, SD 11.4), and weight 45 to 116 kilograms (mean 78.5, SD 19.4).

2.4.2 Variations of Mean Velocity

The overall mean velocities throughout the slight and moderate resistances were not significantly different ($p > 0.05$) between the two wheelchair configurations (Personal vs. PAPAW), and the mean velocities for these conditions were 0.9 m/s for both chairs. However, during the highest resistance trial, individuals showed a significantly lower mean velocity ($p < 0.05$) when using their own manual wheelchair than when propelling with the PAPAW (0.79 m/s, 0.99 m/s respectively).

2.4.3 Metabolic Energy Consumption

The physiologic variables compared between the two wheelchair configurations were: oxygen consumption (VO_2ml/kg x min, VO_2ml/min), ventilation (V_EL/min), and heart rate (BPM). Table 1 shows the means of the four variables, the standard deviation, and the results of the paired t-tests.

Table 1: Results of the Metabolic Testing with the PAPAW and the Subject's Own Manual Wheelchair (Note: NS, not significant)

Trial	VO_2 (ml/min) Mean ± SD		Ventilation (l/min) Mean ± SD		VO_2 (ml/kg*min) Mean ± SD		Heart Rate (bpm) Mean ± SD	
	Personal	PAPAW	Personal	PAPAW	Personal	PAPAW	Personal	PAPAW
0.9 m/s , 10 W	625 ± 316	415±204 p=0.002	19.1±9.0	11.0±5.0 p=0.001	8.0±4.0	5.1±2.4 p=0.004	102±23	91±32 NS
0.9 m/s, 12 W	664±261	415±164 p<0.001	20.2±9.2	11.1±3.5 p=0.001	8.6±3.0	5.3±1.8 p<0.001	99±20	90±33 NS
0.9 m/s, 14 W	855±389	485±199 p<0.001	27.4±11.9	12.5±4.0 p<0.001	10.9±4.6	6.2±2.1 p<0.001	129±30	93±14 p<0.001

One subject was unable to complete a high resistance trial using his or her own manual wheelchair due to fatigue. For oxygen consumption and ventilation, a significant difference ($p < 0.05$) was noted between the two wheelchairs. Mean heart rate was significantly reduced when participants used the PAPAW during the high resistance trial. However, mean heart rate for the slight and moderate resistances was not significantly different between the two wheelchairs. Results of the mixed model ANOVA showed that the PAPAW was responsible for the observed changes in all dependent variables.

2.4.4 Stroke Frequency and Range of Motion

From the kinematic data that were collected, thirteen of the fifteen participant's data could be used. The two kinematic data sets that could not be used were due to excessive marker dropout during the testing, which did not permit proper filtering or analysis with Matlab. The demographics of those that were used were: 10 males and 3 females, age 28 to 52 years (mean 38.5, SD 7.0), height 152 to 193 centimeters (mean 179.6, SD 11.8), and weight 45 to 116 kilograms (mean 78.0, SD 19.8). Table 2 shows the mean stroke frequency for the two wheelchairs throughout all resistance conditions.

Table 2 Subject's Mean Stroke Frequency (strokes/second)

Trial	Personal Wheelchair	PAPAW	Significance
0.9m/s, 10W	0.80	0.64	0.001
0.9m/s, 12W	0.82	0.63	0.001
0.9m/s, 14W	0.74	0.65	0.078

While stroke frequency was significantly reduced ($p < 0.05$) for participants for the slight and moderate resistances, there was no significant difference between the two chairs when resistance was at the highest setting.

Tables 3-5 show the overall range of motion angles for the shoulder, elbow and wrist joints for participants when propelling their own manual wheelchair and a PAPAW.

Table 3: Results of Shoulder ROM Testing with the PAPAW and Subject's Own Wheelchair. Note: Values are given in degrees. NS, not significant

	Flexion/Extension Mean±SD		Internal/External Rot. Mean±SD		Abduction/Adduction Mean±SD		Horizontal Flex/Ext Mean±SD	
Trial	Personal	PAPAW	Personal	PAPAW	Personal	PAPAW	Personal	PAPAW
0.9m/s, 10W	53 ± 11	46 ± 9	40 ± 9	33 ± 8	19 ± 8	15 ± 7	78 ± 16	74 ± 15
	p = 0.003		p = 0.032		NS		p = 0.028	
0.9m/s, 12W	53 ± 10	44 ± 8	42 ± 8	36 ± 6	21 ± 8	16 ± 8	78 ± 14	70 ± 16
	p = 0.005		p = 0.002		NS		p = 0.043	
0.9m/s, 14W	61 ± 10	51± 10	45 ± 7	37 ± 6	20 ± 5	16 ± 6	86 ± 17	77 ± 15
	p = 0.003		p = 0.001		NS		p = 0.009	

Table 4: Results of Wrist ROM Testing with the PAPAW and Subject's Own Wheelchair. Note: Numbers are in degrees. NS, not significant

	Flexion/Extension Mean±SD		Supination/Pronation Mean±SD		Ulnar/Radial Deviation Mean±SD	
Trial	Personal	PAPAW	Personal	PAPAW	Personal	PAPAW
0.9m/s, 10W	44 ± 10	41 ± 12	50 ± 14	48 ± 10	37 ± 10	33 ± 7
	NS		NS		p = 0.028	
0.9m/s, 12W	46 ± 11	43 ± 9	56 ± 15	50 ± 12	38 ± 10	32 ± 9
	NS		p = 0.008		p = 0.014	
0.9m/s, 14W	51 ±12	44 ± 11	64 ± 15	52 ± 11	44 ± 11	36 ± 7
	p = 0.019		p = 0.001		p < 0.001	

Table 5: Results of Elbow ROM Testing with the PAPAW and Subject's Own Wheelchair. (Note: Numbers are in degrees. NS, not significant)

	Flexion/Extension Mean±SD	
Trial	Personal	PAPAW
0.9m/s, 10W	47 ± 9	42 ± 7
	NS	
0.9m/s, 12W	47 ± 9	44 ± 8
	NS	
0.9m/s, 14W	56 ± 8	45 ± 9
	$p < 0.001$	

During propulsion at the slight resistance, paired sample t-tests showed significantly lower ($p < 0.05$) range of motion when using the PAPAW for: shoulder flexion/extension, internal/external rotation, horizontal flexion/extension, and wrist ulnar/radial deviation. At the moderate resistance, a significant decrease in range of motion was observed for shoulder flexion/extension, internal/external rotation, horizontal flexion/extension, forearm supination/pronation, and ulnar/radial deviation. At the highest resistance, there were significant decreases in overall range of motion when using the PAPAW for all joint movements except for shoulder abduction/adduction.

2.5 DISCUSSION

The need for maintaining functional, independent mobility is extremely important among MWUs. It is common for an individual with tetraplegia, particularly one who is several years post injury, to transition from using a manual wheelchair to a powered mobility device. Reasons for this include: weight gain, upper extremity injuries and pain from overuse, and overall decreased physical capacity. However, there are numerous factors to consider when deciding on a mobility device, and switching from one device to another could have a significant impact on the individual's lifestyle. For example, a MWU who is considering transition to an electric powered wheelchair may not have a home environment or an accessible vehicle that would accommodate such a device. Here again, a PAPAW would offer an alternative solution to a powered mobility device.

Maintaining a certain level of activity with manual wheelchair propulsion could also benefit the person's overall physical capacity. Reduced physical capacity in MWUs with tetraplegia occurs for several reasons, including: reduced function in the upper extremities, impaired sympathetic cardiac regulation, and decreased venous return.[33] As this testing revealed, when using a PAPAW, participants showed decreased physical exertion while maintaining, or even improving, their propulsion velocity. The importance of this cannot be understated. For individuals with decreased physical capacity, conserving energy during routine tasks, such as propelling uphill or across a carpeted hallway, might allow an individual to maintain function while performing other necessary activities, such as transferring to a different surface.

The prevention of upper extremity pain and repetitive strain injuries (RSIs) in MWUs is extremely important since both can severely limit an individual's ability to maintain functional, independent mobility. Limiting excessive joint range of motion and high stroke frequency could potentially decrease the likelihood for developing pain and injuries. For this testing, the range of motion and stroke frequency of individuals stayed the same throughout the trials when using the PAPAW. Even at the high dynamometer resistance, little change in the stroke frequency or range of motion was observed. This reflects the proportional nature of the assistance that the PAPAW provides. As the difficulty of the trials increases, the amount of assistance provided by the PAPAW increases, and the individual's effort remains the same.

Stroke frequency was not significantly different between the two chairs when resistance was at the highest setting. Furthermore, the stroke frequency for the participants lowered during the most difficult trial when using their own wheelchair. This seems counterintuitive, since one would expect the user to increase their cadence as the physical demands of the task increased. A possible cause of this is that some participants were fatiguing at the high resistance and not maintaining the target 0.9 m/s when pushing their own manual wheelchair. Therefore, they were propelling less often than in previous trials. This was confirmed, since there was a significant difference in velocity observed between the two wheelchairs at the highest resistance ($p = 0.009$).

As mentioned earlier, avoiding propulsion positions where the shoulder joint is excessively flexed in the sagittal plane, and decreasing the amount it is abducted is desirable. When looking at the overall range of motion angles, there was a significant difference for shoulder flexion/extension but not for abduction/adduction. When the range of motion was broken down into individual movements, there was no significant reduction in shoulder abduction when using a PAPAW. However, there was a significant difference in mean shoulder flexion ($p < 0.05$) for all conditions. Gellman suggested that the high prevalence of carpal tunnel syndrome was caused by the combination of repetitive trauma to the extended wrist while propelling combined with the forced extension of the wrist when performing pressure reliefs.[8] Therefore, avoiding positions where the wrist is in extreme extension could further prevent the development of carpal tunnel syndrome. As revealed in the results, there was only a significant change in overall wrist flexion/extension during the high resistance between the two wheelchairs. However, when the wrist movement was broken down between flexion and extension, there was a significantly lower extension angle ($p < 0.05$) for the PAPAW during all resistance conditions ($p = 0.006$, 0.002, and 0.005). Thus, the PAPAW showed a decrease in wrist extension during propulsion.

The set position that was taken for each trial showed no significant difference ($p > 0.05$) between the location of the hub marker and the participants' acromion process. We concluded with the use of a mixed model ANOVA that the PAPAW was the likely cause for change in the dependent variables. Future studies with this device should focus on the ability of MWUs with tetraplegia to perform necessary activities of daily living within their home environment and community.

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3.0 PHASE II: EFFECT OF A PUSHRIM ACTIVATED POWER ASSIST WHEELCHAIR ON THE FUNCTIONAL CAPABILITIES OF INDIVIDUALS WITH TETRAPLEGIA

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3.1 ABSTRACT

The purpose of the second phase of the study was to test the differences between a pushrim activated power-assisted wheelchair (PAPAW) and a traditional manual wheelchair for individuals with tetraplegia while performing common driving activities. This was a repeated measures study and was conducted in an Activities of Daily Living (ADL) driving laboratory within a Veterans Affairs medical center. Fifteen fulltime manual wheelchair users with tetraplegia participated in the study.

Participants propelled both their own manual wheelchairs and a PAPAW three times over an activities of daily living course. Each participant's heart rate was monitored throughout the testing. Time was recorded to complete the course, and the participants were asked to fill out a visual analog scale based survey after the first, third, fourth and sixth trial to determine the ease of completing each obstacle, and their ergonomic preferences among the two wheelchairs. Additionally, participants were observed throughout trials to determine the amount of assistance needed to complete each obstacle.

Ten out of the eighteen obstacles included in the ADL course were rated as being significantly easier to complete when using the PAPAW. Additionally, when using the PAPAW, participants showed a significant ($p < 0.05$) decrease in mean heart rate throughout all trials. The overall time to complete the ADL course was not significantly different between the two wheelchairs. For individuals with tetraplegia, PAPAWs have the potential to improve the functional capabilities during certain activities of daily living, especially when propelling up ramps, over uneven surfaces, thick carpet, and for extended distances.

3.2 INTRODUCTION

Manual wheelchair users (MWUs) with cervical level spinal cord injuries (tetraplegia) often find it difficult to independently complete certain activities of daily living (ADLs). The reasons for this can be attributed to reduced physical capacity, upper extremity muscle weakness, pain, injuries, or fatigue due to overexertion from propelling a manual wheelchair throughout the day. The capacity of MWUs to perform ADLs is affected by several different variables, including: the environment of the individual, the functional capabilities of the individual, and the assistive technology being used to complete the task.

When using a manual wheelchair as one's primary means of mobility, performing necessary activities of daily living can put significant stresses on the upper extremities. It is therefore common for these individuals to experience pain and injuries. Pentland stated that the ability of manual wheelchair users to maintain high levels of independence in performing activities of daily living hinges on the integrity of upper extremity bones, joints and soft tissues.[1] Curtis discussed the prevalence of shoulder pain among manual wheelchairs users during the performance of typical daily activities.[2] In this cross-sectional survey study, 192 participants with both tetraplegia and paraplegia rated the level of their shoulder pain on a visual analog scale during certain activities. Activities during which individuals with tetraplegia reported high incidences of shoulder pain included: pushing a wheelchair up an incline, pushing for more than ten minutes, and sleeping. Additionally, 78% of individuals with tetraplegia noted having some form of shoulder pain since becoming a manual wheelchair user. This was a significantly higher reported incidence than those with paraplegia. Sie also concluded that manual wheelchair users with tetraplegia are much more prone to shoulder pain than those with paraplegia.[3]

Several protocols have been developed to assess the functional capabilities of individuals with disabilities. An often-used test is the Functional Independence Measure (FIM). While the FIM shows good interrater reliability for testing individuals with disabilities and their ability to complete basic ADLs[4], it is a test designed to evaluate a broad range of disabilities and is positively biased towards those who can ambulate. In fact, individuals score lower on the FIM when they use a wheelchair to complete tasks. Other protocols have been developed to specifically test wheelchair users and their ability to complete ADLs. Cress *et. al.* developed the Wheelchair Physical Functional Performance (WC-pPFP) test, an assessment that measures a MWU's ability to complete 11 mobility tasks.[5] Stanely *et. al.* developed the Wheelchair User Functional Assessment (WUFA) scale to test manual wheelchair users in thirteen different functional tasks: maneuvering in a tight space, uneven terrain, door management, street crossing, propelling up a ramp, propelling up a curb, bed transfer, toilet transfer, floor transfer, bathing, upper and lower dressing, reaching function, and picking up objects.[6] While the WUFA showed good interrater reliability, to date, only five subjects have been tested with this scale, none of which had tetraplegia. Another scale that has been developed and tested is the Wheelchair Skills Test (WST).[7] This test, developed by Kirby *et. al.* is similar to the WUFA, but includes 33 tasks with a wide range of skills; from as easy as applying the brakes to more difficult tasks such as performing a wheelie. Kirby's pilot study showed the WST to have good reliability, concurrent validity, and content validity. A further advantage of this assessment tool is that it can be administered in a short session (mean time to complete test was about 30 minutes). Though easy to administer, valid, and reliable, here again, few MWUs with tetraplegia have been tested with the WST.

Due to decreased physical capacity and impaired upper extremities, MWUs with tetraplegia are typically less efficient than MWUs with paraplegia. Beekman *et. al.* showed that, when propelling a wheelchair under controlled conditions, individuals with tetraplegia travel less distance with a higher oxygen consumption rate than those with paraplegia.[8] Thus, a more efficient manual mobility device may simultaneously allow MWUs with tetraplegia to travel further distances while exerting less energy. Furthermore, for any individual, a manual wheelchair is not an efficient means of mobility. With values of gross mechanical efficiency rarely exceeding 10%, alternative methods of manual wheelchair mobility have been proposed.[9,10] Some alternative devices discussed by Van der Woude included a variety of crank-propelled and lever-propelled wheelchairs.[11] While more efficient than manual wheelchairs, these alternative devices are typically more useful for outdoor mobility and have fallen short in presenting feasible and commercially appealing solutions.[12,13]

Pushrim Activated Power Assist Wheelchairs (PAPAWs) offer an alternative between manual wheelchairs, lever-drive systems, and powered mobility devices. These devices are typically manual wheelchairs with a motor linked to the pushrim in each rear hub, where the user's manual pushrim input is supplemented proportionally by the motor **(see Figure 1)**. Propulsion and braking assistance are provided for both forward and rearward travel. While there have been several studies performed with PAPAWs, participants included in previous studies have been limited to either MWUs with thoracic level spinal cord injuries (paraplegia), multiple sclerosis, or no disability.[14-17]

Very few studies have been performed that assess the functional capabilities of MWUs when using a PAPAW to complete tasks that reflect necessary ADLs. Cooper *et. al.* tested MWUs when using a PAPAW over an ADL driving course.[17] However, the participants included in this study were individuals with paraplegia, and the tasks included in the study were limited. Best *et. al.* compared a PAPAW to a manual wheelchair using the WST.[18] Though there was positive feedback from individuals when using the PAPAW, this was a pilot study, and the participants used in the study had no disability. No study to date has been conducted that focuses on ADL task completion of MWUs with tetraplegia, a population who may significantly benefit from PAPAWs.

The purpose of the second phase of this study was to compare the functional differences of MWUs with tetraplegia when propelling a PAPAW and their own manual wheelchair over an ADL driving course. The ADL course was constructed to include obstacles and tasks that have been described in previous studies, which reflect those that are typically encountered by MWUs.[6,7,17] The variables compared between the two wheelchairs included: mean heart rate during each trial, the time to complete the course, the participants perceived level of difficulty in completing each task, and ergonomic comparisons between the two wheelchairs.

3.3 METHODS

3.3.1 Subject Recruitment

Participants were recruited through the Human Engineering Research Laboratories' registry. They were initially contacted by either letter or telephone. All participants had to be between the ages of 18 and 65, full-time manual wheelchair users for at least three months, have a cervical level spinal cord injury (tetraplegia), be currently free from pressure sores and shoulder pain that would prevent them from propelling a manual wheelchair, and have no reported history of cardiopulmonary disease.

3.3.2 Experimental Protocol

Participants were asked to propel both their own manual wheelchair and a PAPAW three times (six total trials) over an ADL simulation course. The protocol and layout of the course is similar to that described by DiGiovine *et. al.*; however, more obstacles have been added.[19] Participants were instructed to complete the course at a comfortable pace (i.e. freely chosen speed). The course was constructed indoors on a tile floor and consisted of the following eighteen obstacles:

- Propelling down a 61 meter tiled hallway
- Opening and going through a door with an accessible handle
- Propelling across a 2.4 meter strip of high pile carpet
- Propelling across a 2.4 meter dimple strip (guide strip for individuals with visual impairments.)
- Propelling up and down a 4 degree sloped ramp that was 6.7 meters long
- Propelling over a sinusoidal bump that was 50 mm high (simulating a speed bump)
- Propelling up a 1.2 meter long , 7.3 degree curb cut
- Propelling up and down a 5.1 centimeter high curb
- Propelling over a door threshold
- Propelling across a deck surface
- Maneuvering through a tight bathroom setup (toilet, sink and bathtub)
- Turning on a kitchen faucet
- Picking up a can of soup and placing it in a different location
- Maneuvering into a simulated bus docking space (0.76 meters x 1.2 meters)

Figure 4 shows a photograph of several of the obstacles included in the study.

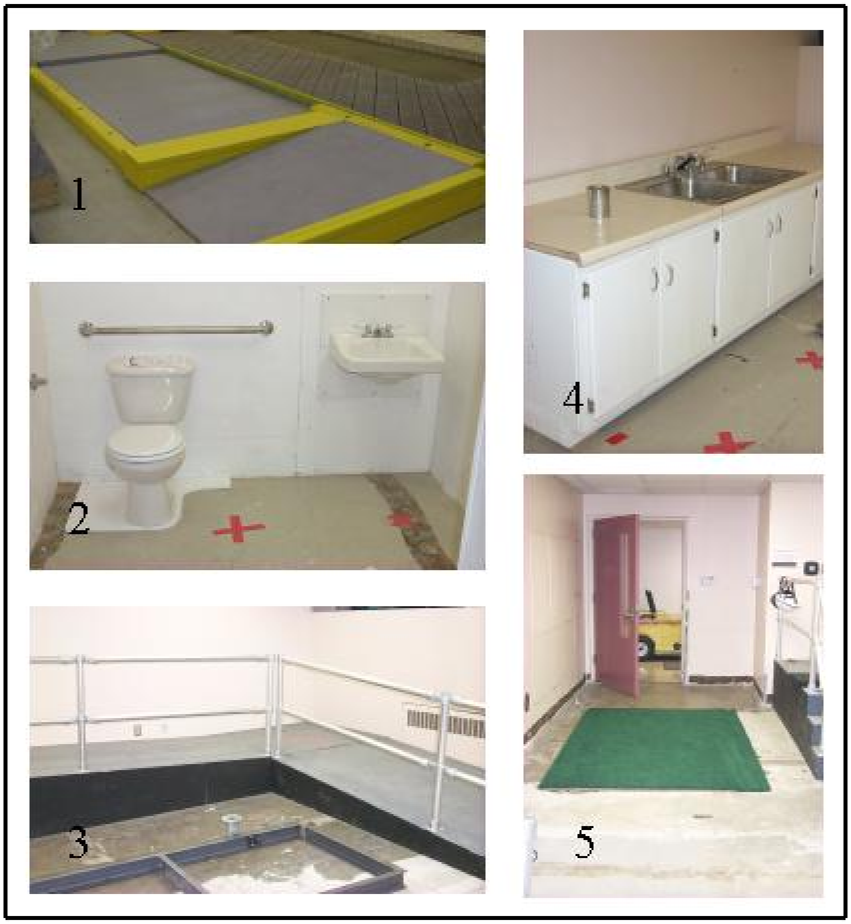

Figure 4. Photos of some of the obstacles included in the ADL course: (1) curb cut, 5.1 cm curb, and deck surface, (2) toilet and bathroom sink, (3) ramp, (4) can of soup and kitchen sink, and (5) door and carpet.

Participants were provided an opportunity to familiarize themselves with the ADL course prior to testing, and colored tape on the floor was used to mark the direction of the driving course. Participants were given at least 30 minutes to rest after the third trial, when they were switching between the two wheelchairs (Own and PAPAW). Following the last trial with the PAPAW, participants were asked to remove the battery and replace it with a spare battery.

The PAPAW available for this study was a Yamaha JWII[a] mounted to a Quickie 2[b] folding frame manual wheelchair. Each Quickie 2 was selected and adjusted to best match each participant's current wheelchair seat dimensions (seat width, seat depth, backrest height, seat to footplate length, pushrim diameter, rear wheel diameter, and axle position). The order in which the wheelchairs were presented was randomized. For safety purposes, a spotter followed each participant throughout the course and provided assistance when requested by the participant. Additionally, a second investigator videotaped the participants throughout the trials to monitor data collection. The learnability of the PAPAW and the ADL course were examined by comparing the results of trial one to the results of trial three, in addition to reviewing the results of the ergonomic questions from the survey.

3.3.3 Participant Survey and Tester Rating Survey

After the first, third, fourth and sixth trial, participants were asked to fill out a portion of the survey questioning certain aspects of the wheelchair or the ADL driving course. The survey consisted of three parts: (1) questions pertaining to the difficulty of completing the obstacles, (2) questions pertaining to the ergonomics of the wheelchairs, and (3) questions specifically related to the PAPAW. The questions pertaining to the completion of obstacles employed a visual analog scale of ten centimeters (cm) in length. The scale ranged from extreme ease on the left (0 cm) to extreme difficulty on the right (10 cm). Participants were asked to place an "x" on the visual analog scale to represent their level of ease/difficulty with each activity within the course for each wheelchair (PAPAW versus Own). Participants were asked to rate the difficulty of completing each obstacle after the first, third, fourth, and sixth trials. The questions pertaining to the ergonomics of the two wheelchairs also contained visual analog based questions and were completed after the third and sixth trial. The third section, which included questions specific only to the PAPAW, was completed after the participant's last trial using the PAPAW.

In addition to the spotter and the videographer, a third investigator observed each the participant and rated their ability to complete each obstacle. A rating scale was used to determine the amount of assistance (if any) that was required by the participant to complete each obstacle. The tester was able to select from one of six choices for each obstacle ranging from "unable to complete" to "independent operation". This third investigator also served as the timekeeper, and used a digital stopwatch to record the overall time for each trial.

3.3.4 Heart Rate Data Collection

Each participant's heart rate was recorded continuously during all of the testing, and was monitored one minute prior to the start of each trial. The heart rate was recorded using a Polar heart rate monitor.[c] This is a chest strap style heart rate monitor, which relays it's signal to a watch, which was placed on the participant's wheelchair.

3.3.5 Statistical Analysis

A single investigator measured the position of the X marked by participants on the visual analog scale questions from the survey. Descriptive statistics were performed for all variables, and histograms were evaluated for normal distributions. Initially, a within-test repeated measures was performed to determine if any significant differences in obstacle completion occurred due to the participants learning the ADL course. A repeated measures test was used to ensure that differences observed in completing the obstacles was not occurring due to a learning effect of the ADL course, but because of differences when propelling the two different wheelchairs. Following this, paired sample t-tests ($p < 0.05$) were used to compare the means of data that was normally distributed, and Wilcoxon Rank Sum tests were performed on data that were not normally distributed. In addition, a mixed model analysis of variance (ANOVA) was used to determine if differences existed between the two types of wheelchairs. A mixed model was used since it allows for comparison between the two wheelchairs even though the same participant performed the testing of the wheelchairs. Statistical analysis was performed using both SPSS[f] and SAS software.[g]

3.4 RESULTS

3.4.1 Participants

This study received prior approval by the appropriate human studies institutional review boards. Each participant was provided with information about the safety and intent of the tests, and signed informed consent was obtained prior to any testing. Fifteen full-time manual wheelchair users (MUWs) with tetraplegia participated in the testing. The demographics included: 11 males and 4 females, age 20 to 53 years (mean 36.0, SD 8.3), height 152 to 193 centimeters (mean 178.1, SD 12.3), and weight 45 to 114 kilograms (mean 77.7, SD 20.9). Additionally, the number of years post injury for participants ranged between 0.82 and 29.27 years (mean 11.8, SD 8.1).

3.4.2 Survey Results

Table 6 shows the overall mean ratings for each obstacle for the PAPAW and the individuals own manual wheelchair, in addition to the significant differences that were observed throughout the testing.

Table 6 Participant ratings of the degree of difficulty to complete obstacles when using their own wheelchair and a PAPAW

Obstacle	First Trial		Third Trial	
	Own	PAPAW	Own	PAPAW
1. Hallway	1.4 ± 1.8	0.6 ± 0.7	1.6 ± 2.0	**0.4 ± 0.3**
2. Door	2.1 ± 2.0	1.6 ± 1.1	1.8 ± 2.1	1.0 ± 0.7
3. Carpet	4.2 ± 2.2	**1.0 ± 1.1**	3.5 ± 2.8	**0.7 ± 0.7**
4. Dimple strips	2.6 ± 2.1	**0.8± 0.8**	2.1 ± 1.7	**0.6 ± 0.6**
5. Up the ramp	5.2 ± 2.7	**1.5 ± 0.9**	5.2 ± 3.0	**0.9 ± 0.7**
6. Down the ramp	2.0 ± 2.5	1.2 ± 0.9	1.7 ± 2.2	0.8 ± 1.0
7. Speed bump	3.3 ± 2.4	2.0 ± 1.2	3.0 ± 2.3	**1.1 ± 0.9**
8. Curb cut (up)	5.5 ± 3.1	**2.1 ± 1.6**	5.2 ± 3.1	**1.1 ± 0.7**
9. 2” Curb (down)	2.2 ± 2.1	1.8 ± 1.4	2.0 ± 1.7	1.1 ± 1.0
10. 2” Curb (up)	5.3 ± 3.0	3.9 ± 2.8	5.5 ± 3.3	**3.6 ± 3.0**
11. Door threshold	2.6 ± 2.4	1.4 ± 1.9	2.7 ± 2.5	**0.7 ± 0.7**
12. Deck surface	1.9 ± 1.7	0.8 ± 0.7	1.7 ± 1.7	**0.5 ± 0.4**
13. Toilet	1.7 ± 1.5	1.1 ± 0.9	1.5 ± 1.6	0.6 ± 0.5
14. Bathroom sink	1.6 ± 1.5	1.3 ± 1.0	1.6 ± 1.8	0.6 ± 0.5
15. Bathtub	1.7 ± 1.6	1.4 ± 1.2	1.6 ± 1.7	1.1 ± 1.2
16. Kitchen faucet	1.6 ± 1.5	1.2 ± 1.0	1.7 ± 1.7	**0.6 ± 0.6**
17. Kitchen counter (can)	2.1 ± 1.7	1.5 ± 1.2	1.9 ± 1.7	0.9 ± 1.3
18. Bus space	1.6 ± 1.6	1.8 ± 1.7	1.6 ± 1.7	1.1 ± 1.3

Note: Values presented as means ± standard deviation. Obstacles that were significantly different ($p < 0.05$) are indicated in bold. For each question on the Visual Analog Scale: 0 = Extremely Easy, 10 = Extremely Difficult.

After the first trial, participants rated four obstacles to be significantly easier ($p < 0.05$) to complete when using the PAPAW: carpet, dimple strips, propelling up the ramp, and propelling up the curb cut. After the third trial, participants rated ten obstacles to be significantly easier to complete when using the PAPAW: hallway, carpet, dimple strips, up the ramp, bump, up the curb cut, up the two inch curb, door threshold, deck surface, and turning on the kitchen faucet. When comparing the PAPAW to itself, between the first and third trial, users rated eight obstacles to be significantly easier to complete: carpet, up ramp, bump, curb cut, toilet, bathroom sink, turning on the kitchen faucet, bus docking space. Table 7 shows the average rank of participants' responses to the ergonomic survey questions when using their own wheelchair and a PAPAW.

Table 7: Participants responses to the ergonomic questions when using their own wheelchair and a PAPAW

Ergonomics Question	Third Trial	
	Own	PAPAW
1. How supported and stable did you feel?	7.2 ± 1.9	6.8 ± 2.2
2. How easy was it to propel the wheelchair?	4.0 ± 2.6	**1.3 ± 1.9**
3. How easy was it to maneuver the wheelchair?	3.6 ± 2.7	2.2 ± 1.8
4. How easy was it to control the wheelchair?	3.6 ± 2.6	3.0 ± 2.0
5. How comfortable was your hand on the pushrim?	5.8 ± 2.9	**7.9 ± 1.6**
6. How would you rate the overall ride comfort?	6.6 ± 2.1	7.5 ± 1.2
7. Rank this wheelchair based on looks.	7.1 ± 2.4	6.4 ± 2.0

Note: Values presented as means ± standard deviation. Obstacles that were significantly different ($p < 0.05$) are indicated in bold. For Question 1 on the Visual Analog Scale: 0 = Not at All, 10 = Extremely. For Questions 2-4 on the Visual Analog Scale: 0 = Extremely Easy, 10 = Extremely Difficult. For Question 5 on the Visual Analog Scale: 0 = Not at all, 10 = Extremely. For Questions 6-7 on the Visual Analog Scale: 0 = Poor, 10 = Excellent

After the third trial, participants reported that the PAPAW was significantly easier ($p < 0.05$) to propel and the pushrim was more comfortable than their own manual wheelchair. The averages of participants' responses to questions pertaining only to the PAPAW after the third trial are shown in Table 8.

Table 8: Participants responses to the questions specifically directed to using the PAPAW

Use of PAPAW Question	Rank after Third Trial
1. How understandable is the power switch?	6.0 ± 2.4
2. How understandable are the buzzer sounds?	5.5 ± 2.2
3. How understandable are the LED signals?	4.9 ± 2.3
4. How easy was it to remove the battery?	3.4 ± 3.3
5. How easy was it to put on the spare battery?	4.1 ± 3.5

Note: Values presented as means ± standard deviation. For the questions on the Visual Analog Scale: 0 = Not at All, 10 = Extremely

The type of assistance that was needed by the participants during testing could be categorized into three groups: (1) independent operation, where the individual was able to complete the task without assistance; (2) close spotting, where the individual performs the task, but is required to have an assistant readily at hand; and (3) directed assistance, where the individual is physically unable to complete the test, but is able to direct the spotter in completion of the task. For the most part, participants were able to complete the obstacles independently. For all trials, the total number of times that participants needed to be closely spotted when using their own wheelchair was five. When using the PAPAW, participants needed to be closely spotted three times. Additionally, participants needed directed assistance in completing tasks a total of 35 times with their own wheelchair and 14 times when using the PAPAW.

3.4.3 Heart Rate and Time to Complete Course

For all three trials, mean heart rate was significantly lower ($p < .05$) when using the PAPAW when compared to the participant's own manual wheelchair. Table 9 shows the mean heart rate values for each wheelchair and trial, as well as the average times to complete the ADL course.

Table 9: Mean Heart Rate During Trials and ADL Course Completion Times

Variable	Trial 1		Trial 2		Trial 3	
	Own	PAPAW	Own	PAPAW	Own	PAPAW
Mean Heart Rate (BPM)	94 ± 12.8	**84 ± 13.2**	90 ± 11.4	**83 ± 12.2**	90 ± 12.6	**84 ± 14.8**
Time to complete course (s)	226 ± 46.5	228 ± 56.8	216 ± 41.1	202 ± 33.4	209 ± 42.4	196 ± 26.3

Note: Values presented as means ± standard deviation. Variables that were significantly different ($p < 0.05$) are indicated in bold.

Though the overall mean time when using the PAPAW was slightly lower than when using the participants' own wheelchair (215 seconds versus 209 seconds), there was no significant difference in the mean time to complete the course between the two wheelchairs. Additionally, the participants showed a greater drop in mean time to complete the course from the first trial to the third trial (32 seconds versus 22 seconds) when using the PAPAW versus their own wheelchair.

3.5 DISCUSSION

Maintaining an active lifestyle, where participating in community activities is a priority, can have a positive influence on life satisfaction among individuals with disabilities.[20] With MWUs, the amount of social integration which takes place can be influenced by the effectiveness with which they propel their manual wheelchair through a variety of environments (e.g. slopes, rough or uneven terrain, long distances, heavy carpeting). The prevention of upper extremity pain and repetitive strain injuries (RSIs) in MWUs is extremely important since both can severely limit an individual's ability to maintain independent mobility and function within ADLs. Pentland noted that many of the activities that commonly elicited shoulder pain in

MWUs (ie transfers, propelling long distances, driving, outdoor propelling) are also activities that allow interaction in the community and are important for independence and self esteem.[1]

Following a similar pilot study, Cooper suggested that future ADL lab testing with PAPAWs should include individuals with impaired upper extremities, more difficult tasks, and an older population of participants. [17] This was primarily suggested because, in the pilot study, participants were individuals with paraplegia, and there were no significant differences between PAPAWs and participants' own manual wheelchairs for the majority of the variables tested. In the current study, more tasks were included, and the participants selected had impaired upper extremities, since they had tetraplegia. However, the mean age of the population that was tested in the current study was still rather young (mean 36.0 years). This can likely be attributed to MWUs with tetraplegia transitioning to powered mobility devices as they get older. The majority of potential, older participants that we contacted either had been using a power wheelchair since their injury or had already transitioned from their manual wheelchair to a power wheelchair.

Results from the survey portion of the testing were consistent to Cooper's suggestion that a population group with impaired upper extremities would prefer the PAPAW to their own manual wheelchair. By the third trial, participants rated 10 of the 18 obstacles significantly easier to complete when using the PAPAW. Interesting to note were the differences observed between PAPAWs from the first trial to the third trial, and the obstacles that were rated as being significantly easier by the participants. Results from the survey suggested learning curve when using the PAPAW, since participants rated eight obstacles to be significantly easier to complete from the first to the third trial when using the device. Three of these tasks can be construed as maneuvering in tight areas: two bathroom tasks, the toilet and the sink, and maneuvering into the bus-docking situation. This revealed that the users were becoming more comfortable maneuvering the PAPAW in tight spaces, and after only using it for a few minutes.

The higher rating that the PAPAW received for the ease of propulsion question is also intuitive, given the assistance that the wheels provide. Interestingly, a higher level of pushrim comfort was also indicated by the participants when using the PAPAW. This could possibly be attributed to participants exerting less effort on the pushrims when propelling the PAPAWs. As mentioned previously, the number of times that participants needed assistance when completing tasks was decreased when using the PAPAW. The tasks, in particular, where participants showed significant improvement (i.e. going from needing assistance to completing the task independently), were propelling up the ramp and up the curb cut. This can be attributed to the assistance provided by the PAPAW. Removing and replacing the battery from the PAPAW presented as a difficult task for participants, and could be a redesign consideration for this particular power assist wheelchair.

The heart rate data that was collected also revealed beneficial results for participants when using the PAPAW. MWUs with tetraplegia are often observed to have reduced physical capacity due to: reduced function in the upper extremities, impaired sympathetic cardiac regulation, and decreased venous return.[21] The results of this testing revealed that participants were able to complete the ADL course in the same amount of time between the two wheelchairs, but maintained a lower heart rate when using the PAPAW. Conserving energy during routine tasks, such as propelling uphill or across a carpeted hallway, might allow a MWU with tetraplegia to maintain function while performing other necessary activities, such as transferring to a different surface.

Certain manual wheelchair skills that have been included in previous studies were omitted for this testing. Some of these tasks included: transfers, performing wheelies, applying the brakes, and removing footrests. Transferring from the wheelchair to a different surface was not tested because we believed that, when provided with identical wheelchair setups, participants would perform the transfers similarly. Furthermore, the ability of an individual to transfer to a different surface is controlled by two factors: the setup of the wheelchair (e.g. floor to seat height, amount of seat angle, height of the wheels, etc.), and the functional capability and technique of the individual performing the transfer. When provided with an ideal wheelchair setup, neither of these factors would be influenced by an individual using a PAPAW. Additionally, we did not anticipate every participant to be completely independent in performing transfers, and this was observed to be true when participants were transferring between the two wheelchairs. Applying the parking brakes and removing footrests is also wheelchair specific and, similar to transferring, not necessarily a task that would be affected by using a PAPAW. The ability to perform wheelies was left out for safety reasons. It is recommended by the manufacturer that individuals who are unfamiliar with a power assist wheelchair use the anti-tippers initially to prevent from tipping over backwards in the wheelchair. For this reason, and for time constraints, we believed that it was safer to test the PAPAWs with anti-tippers. It should be noted that even with the anti-tippers attached to the PAPAW, participants were able to propel over the 5.1 cm curb.

Results of the repeated measures statistical testing showed that there were no significant differences due to participants learning the ADL course. From this, combined with the results of the mixed model ANOVA, we concluded that propelling the PAPAW was the cause of observed differences in dependent variables. Although the ADL course was built to duplicate predicted obstacles that a MWU would encounter throughout the course of a day, a more thorough test of the PAPAW's ability to improve the functional capabilities of MWUs with tetraplegia would be to allow individuals to take the wheelchair home with them for several weeks.

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4.0 SUMMARY

The stated goal of this study was to determine if a PAPAW could have a positive impact on the propulsion demands and functional capabilities of individuals with tetraplegia. It was encouraging to observe an overall decrease in the physical demands of wheelchair propulsion for the participants when using the PAPAW. What was further encouraging was the fact that they were propelling with less effort, while maintaining or improving their speed and ADL task completion capabilities. The findings presented in this paper have expanded the knowledge of how PAPAWs can positively influence the propulsion capabilities and ADL task completion of individuals with tetraplegia. For individuals with disabilities, PAPAWs offer a unique alternative to manual and powered wheelchairs. However, the tasks presented in this testing are not all inclusive for obstacles that may be faced by MWUs with tetraplegia and there are some limitations to this study.

The relatively short propulsion trials during the first phase might not allow all participants to reach steady state. However, we noted that several of the participants were fatiguing when using their own manual wheelchairs, and after only propelling for three minutes. We also observed that the metabolic data had reached a plateau for the majority of participants that were tested. Combined with the knowledge that we were working with a population with decreased physical capacity, we felt that three minutes was a sufficient propulsion trial length. It should be noted that upper extremity joint range of motion and stroke frequency are not the sole factors contributing to pain and repetitive strain injuries. Other factors, such as the forces applied by the wheelchair user at the pushrim should be considered as well. Future biomechanics studies with this device and subject population should investigate the forces and moments that occur at the joints when propelling.

Tasks that should have been included in the second phase of the study were: closing the door and transferring the wheelchairs into a car. Additionally, a longer strip of carpet would have provided the participants with further feedback on how the PAPAW provides assistance when propelling over high resistance surfaces. Because of the limitations in the size of the driving course, this obstacle could not be lengthened. Tasks that were not included, such as transferring into a car, will likely be addressed during a home evaluation of the PAPAW. Another limitation was the male biased population and relatively young age of participants in both phases of the study. Future studies should include a more diverse population, including manual wheelchair users who are older. The videotapes taken during the testing should be reviewed by an independent clinician to confirm the amount of assistance that was required by participants to complete certain obstacles. Additionally, a second, independent investigator should verify the distance measured by the first investigator on the visual analog scale.

Finally, propulsion efficiency and ADL task completion are not the only factors that should be considered when addressing one's overall seating and mobility needs. PAPAWs should be recommended when users can safely and effectively propel them throughout all daily activities and obstacles. While the results of this study yielded positive feedback from the participants when using the PAPAW, a more thorough test of the device's effectiveness would be a home evaluation. Future studies with this device should focus on the ability of MWUs with tetraplegia to perform necessary activities of daily living within their home environment and community.

APPENDIX A

SUPPLIERS

a. Yamaha Motor Co, 2500 Shingai, Iwata, Shizuoka, 438-8501, Japan.

b. Sunrise Medical Corp, Quickie Div, 2842 Business Pk Ave, Fresna, CA 93727-1328.

c. MedGraphics, 350 Oak Grove Pkwy, St. Paul, MN 55127-8507.

d. Polar CIC, Inc, 370 Crossways Park Dr, Woodbury, NY 11797-2050.

e. Northern Digital, Inc, 103 Randall Dr, Waterloo, Ont N2V 1C5, Canada..

f. SPSS Inc, 233 S Wacker Dr, 11th Fl, Chicago, IL 60606-6307.

g. SAS Institute Inc, SAS Campus Dr, Cary, NC 27513-2414.

h. The MathWorks Inc, 24 Prime Park Way, Natick , MA 01760-1500.

APPENDIX B

QUESTIONAIRE USED DURING PHASE II OF THE TESTING

<u>Part A: Activities of Daily Living Course</u>

Please indicate the ease of use of each obstacle by placing an "X" on the accompanying line for each item.

a) A mark on the farthest left-hand point of the line would indicate *Extremely Easy*, while a mark on the farthest right-hand point of the line would indicate *Extremely Difficult.*
b) Points in between the two ends of the line would indicate intermediate values for ease of use
c) If you did not complete the obstacle, or required assistance, please check the appropriate box, and allow the tester to complete that question:

*Example question---place **X** anywhere on line*

Extremely Easy ——X—————————— Extremely Difficult

A1: How does ease of use rate after the first trial when:

<u>1) Propelling down the hallway:</u>

Extremely Easy ———————————— Extremely Difficult

Did not complete: _____
Completed with assistance: ______

<u>2) Opening and entering the door</u>:

Extremely Easy ———————————— Extremely Difficult

Did not complete: _____
Completed with assistance: ______

3) Propelling over the carpet:

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

4) Propelling over the dimple strip:

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

5) Propelling *up* the ramp:

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

6) Propelling *down* the ramp:

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

7) Propelling over the Medium Sized Bump:

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

8) Propelling up the curb cut:

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

9) Propelling down the 2" Curb:

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

10) Propelling up the 2" Curb:

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

11) Propelling up the door threshold:

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

12) Propelling across the deck:

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

13) Propelling up to the toilet:

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

14): Propelling up to the sink (bathroom):

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

15): Propelling up to the bathtub:

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

16) Propelling up to a sink, turning on the faucet in the kitchen

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

17) Propelling up to a countertop in the kitchen, picking up item, replacing it:

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

18) Maneuvering into the bus-space:

Extremely Easy ______________________________________ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

A2: How does ease of use rate after third trial when:

1) Propelling down the hallway:

Extremely Easy ______________________________________ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

2) Opening and entering the door:

Extremely Easy ______________________________________ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

3) Propelling over the carpet:

Extremely Easy ______________________________________ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

4) Propelling over the dimple strip:

Extremely Easy ______________________________________ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

<u>5) Propelling *up* the ramp:</u>

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

<u>6) Propelling *down* the ramp:</u>

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

<u>7) Propelling over the Medium Sized Bump:</u>

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

<u>8) Propelling up the curb cut:</u>

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

<u>9) Propelling down the 2" Curb</u>:

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

<u>10) Propelling up the 2” Curb:</u>

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

<u>11) Propelling up the door threshold:</u>

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

<u>12) Propelling across the deck:</u>

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

<u>13) Propelling up to the toilet:</u>

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

<u>14): Propelling up to the sink (bathroom):</u>

Extremely Easy ____ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

15): Propelling up to the bathtub:

Extremely Easy ______________________________ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

16) Propelling up to a sink, turning on the faucet in the kitchen

Extremely Easy ______________________________ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

17) Propelling up to a countertop in the kitchen, picking up item, replacing it:

Extremely Easy ______________________________ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

18) Maneuvering into the bus-space:

Extremely Easy ______________________________ Extremely Difficult

Did not complete: _____
Completed with assistance: ______

Part B: Ergonomics and comfort

Please place an "X" on the accompanying line that best indicates how you feel about each question related to the wheelchair that you just completed testing.

1) How supported and stable did you feel on this course? (Supported is defined as minimal shifting due to discomfort)

Not at all ______________________________ Extremely

2) How easy was it to propel the wheelchair?

Extremely Easy ———————————————— Extremely Difficult

3) How easy was it to maneuver the wheelchair?

Extremely Easy ———————————————— Extremely Difficult

4) How easy was it to control the wheelchair?

Extremely Easy ———————————————— Extremely Difficult

5) How comfortable was your hand on the pushrim?

Not at all ———————————————— Extremely

6) How would you rate the overall ride comfort?

Poor ———————————————— Excellent

7) Rank this wheelchair based upon its looks.

Poor ———————————————— Excellent

Short answer in the space provided.

1) What do you like most about this wheelchair?

2) Is there anything specific about this chair that you feel adds or subtracts from the overall level of comfort on this course?

Part C: Use of the JWll Survey

Nine situations are stated below which may occur while using the wheelchair with the JWll electric-powered add-on unit. There is also a scheme with possible combinations of power switch position, kind of buzzer sound and kind of blinking of the LED. Each situation corresponds with one of these combinations. Please write the number of the situation besides the combination you think corresponds.

Situations:

1. Turning the power on
2. Turning the power off
3. Turning the power on while force is added to the hand rim
4. When the power is turned off by auto-off function
5. Battery has run out
6. Battery remaining warning (it will soon come to stop assist power)
7. When the safety system works while the power switch is on
8. Malfunction of the electrical device
9. Connector between the right and left wheel is disconnected

Possible combinations:

Power switch	**Buzzer sound**	**LEDs**	**Situation**
on	pi----sound (constantly)	light on	
on	pi----sound (constantly)	light on	
off	pi-sound (1second)	-	
on	pi-sound (1second)	quickly blinking (0.25 cycles)	
off	-	-	
on	pi----sound (constantly)	quick blinking (0.25 cycles)	
on	pi----sound (constantly)	quick blinking (0.25 cycles)	
on	pi-sound (1second)	blinking (3 seconds)	
on	pi-pi-pi-pi- sound	blinking slowly (1 sec. cycles)	

Please place an "X" on the accompanying line that best indicates how you feel about each question related to the wheelchair with JWll power on. Except for question four. You should answer that question in the space provided.

1) How understandable is the power switch to you?

Not at all ____ Extremely

2) How understandable are the buzzer sounds to you?

Not at all ______________________________ Extremely

3) How understandable are the LED signals to you?

Not at all ______________________________ Extremely

Short answer in the space provided.

4) Which of the signals did you notice during the course?

5) How easy was it to take off the empty battery?

Not at all ______________________________ Extremely

6) How easy was it to put on the spare battery?

Not at all ______________________________ Extremely

Thank you for completing this survey!

APPENDIX C

INVESTIGATOR SURVEY USED DURING TESTING

Obstacle:	**Amount of assistance required:**							**Notes:**
1. Hallway:	0	1	2	3	4	5	6	
2. Door:	0	1	2	3	4	5	6	
3. Carpet:	0	1	2	3	4	5	6	
4. Dimple Strips:	0	1	2	3	4	5	6	
5. Up the ramp:	0	1	2	3	4	5	6	
6. Down the ramp:	0	1	2	3	4	5	6	
7. Medium Sized Bump:	0	1	2	3	4	5	6	
8. Curb cut (up):	0	1	2	3	4	5	6	
9. 2” Curb (down):	0	1	2	3	4	5	6	
10. 2” Curb (up):	0	1	2	3	4	5	6	
11. Door threshold:	0	1	2	3	4	5	6	
12. Deck Surface:	0	1	2	3	4	5	6	
13. Toilet:	0	1	2	3	4	5	6	
14. Bathroom Sink:	0	1	2	3	4	5	6	
15. Bathtub:	0	1	2	3	4	5	6	
16. Kitchen Counter (can)	0	1	2	3	4	5	6	
17. Kitchen Faucet:	0	1	2	3	4	5	6	
18. Bus Space:	0	1	2	3	4	5	6	

TIME TO COMPLETE COURSE: ______________

0 = Not tested

1 = Unable: Subject is physically unable, is not able to direct and no person can be identified for training, or requires assistance from more than 1 person

2 = Non Directed Assistance: Subject is physically unable to complete task, and is unable to direct others in steps needed to complete. Requires trained assistant for safe performance.

3 = Directed Assistance: Subject is physically unable to complete task, but is able to direct a casual (non trained) assistant in steps needed to compete task. Performs safely with untrained assistant.

4 = Close Spotting: Subject requires assistant to be closely spotting (prepared to provide physical support) for safety. Performs unsafely.

5 = Verbal Cueing: Subject is physically able to complete task. Requires consistent verbal cues to prevent unsafe performance.

6 = Independent Operation: Subject is able to independently complete the task without physical assistance. Performs safely.