A motor learning approach to training wheelchair propulsion biomechanics for new manual wheelchair users: A pilot study

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Context/Objective: Developing an evidence-based approach to teaching wheelchair skills and proper propulsion for everyday wheelchair users with a spinal cord injury (SCI) is important to their rehabilitation. The purpose of this project was to pilot test manual wheelchair training based on motor learning and repetition-based approaches for new manual wheelchair users with an SCI.

Design: A repeated measures within-subject design was used with participants acting as their own controls.

Methods: Six persons with an SCI requiring the use of a manual wheelchair participated in wheelchair training. The training included nine 90-minute sessions. The primary focus was on wheelchair propulsion biomechanics with a secondary focus on wheelchair skills.

Outcome Measures: During Pretest 1, Pretest 2, and Posttest, wheelchair propulsion biomechanics were measured using the Wheelchair Propulsion Test and a Video Motion Capture system. During Pretest 2 and Posttest, propulsion forces using the WheelMill System and wheelchair skills using the Wheelchair Skills Test were measured.

Results: Significant changes in area of the push loop, hand-to-axle relationship, and slope of push forces were found. Changes in propulsion patterns were identified post-training. No significant differences were found in peak and average push forces and wheelchair skills pre- and post-training.

Conclusions: This project identified trends in change related to a repetition-based motor learning approach for propelling a manual wheelchair. The changes found were related to the propulsion patterns used by participants. Despite some challenges associated with implementing interventions for new manual wheelchair users, such as recruitment, the results of this study show that repetition-based training can improve biomechanics and propulsion patterns for new manual wheelchair users.

Keywords: Manual wheelchair, Propulsion, Spinal cord injury, Training

Introduction

The most common type of wheelchair used for everyday mobility by persons with spinal cord injuries (SCI) is a manual wheelchair.¹ While wheelchair propulsion is an essential skill for maneuvering a manual wheelchair, research suggests that repetitive loading on the upper extremities may contribute to pain and chronic overuse injuries.²⁻⁴ Specifically, biomechanically poor wheelchair propulsion techniques have been associated with rotator cuff injuries, tendonitis, carpal tunnel syndrome, and median nerve injuries.^{5,6} Pain and injury to the upper extremities is a major concern for manual wheelchair users because they depend on their upper extremities to perform typical activities of daily living

(e.g. transferring, getting dressed, and driving a vehicle).^{7,8} New manual wheelchair users may benefit from training in proper wheelchair propulsion to help decrease the possibility of injuries that may affect their mobility and activities of daily living.

The literature contains substantial information regarding wheelchair propulsion mechanics, techniques, and skills. Specifically, research suggests that important components of wheelchair propulsion training are decreasing push frequency, increasing push angle, and using a semicircular propulsion pattern or a pattern in which the hand drops below the pushrim toward the axle of the wheel during the recovery phase of the push.² The Clinical Practice Guidelines for the Preservation of Upper Limb Function Following Spinal Cord Injury (CPG)⁹ recommendations are based upon this research and emphasize minimizing

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the force and frequency of pushes and using long pushes during propulsion.^{2,10} The goal of the guidelines is to promote a more effective propulsion pattern, or a motion that requires fewer pushes on the pushrim but uses more of the pushrim to retain the same speed.¹¹ Increased propulsion effectiveness minimizes unnecessary upper extremity use during propulsion and may be one factor that leads to a reduction in chronic injuries of the upper extremities.

Manual wheelchair users often use propulsion biomechanics that do not follow the recommended guidelines; for example, they may use a propulsion pattern wherein they push with a short push angle and/or do not bring their hands down toward the axle during the recovery phase of the push.^{11,12} Previous research indicates that wheelchair propulsion mechanics and wheelchair skills may be changeable through training.^{13,14} Different approaches to improving propulsion mechanics, including instructional programs based on aspects of motor learning such as visual and verbal feedback, have been researched.^{15–18} Motor learning consists of many components, but one of the most effective approaches to skill acquisition is increasing the number of times a skill is practiced.^{19,20} To teach propulsion biomechanics following the CPG so that proper propulsion can be performed without much thought and with little effort may require many repetitions and training sessions.^{19,21–24}

A relationship between wheelchair propulsion and chronic overuse injuries is documented, clinical guidelines have been developed, and research has been conducted on different approaches to training; however, new manual wheelchair users are often given little formal information or training on how to propel their wheelchairs.¹² Few rehabilitation programs focus on manual wheelchair propulsion training, despite evidence that suggests the benefits of training.^{13,14} Clinicians often report no implementation of formalized protocols or evidence-based practice into wheelchair training rehabilitation because of time, cost, and lack of knowledge.²⁵ When training does occur, it tends to be basic wheelchair training (e.g., addressing wheelchair use, propulsion, and navigating obstacles) for an average of one to four hours during the entire rehabilitation stay.²⁵ This limited time would not allow for specific propulsion instruction or practice time.

Developing evidence-based approaches to teaching wheelchair skills and proper propulsion for people with SCI is important for successful rehabilitation for everyday wheelchair users. The purpose of this pilot study was to test a manual wheelchair training program based on motor learning principles for manual wheelchair users with SCI. We hypothesized that, after participants

received the wheelchair training intervention, they would increase their push angle, use a semicircular push pattern, decrease push force, increase push effectiveness, and improve wheelchair skills proficiency.

Methods

Participants

Six persons (four men, two women; average age, 38 ± 17.5) with an SCI requiring the use of a manual wheelchair participated in this study were recruited to help determine the feasibility of the training program. Participants were recruited through local rehabilitation facilities in the Midwestern region of the United States (Table 1). Fifty percent of participants reported still receiving outpatient rehabilitation services and that these services did not specifically address wheelchair propulsion or wheelchair skills. Participants were screened to ensure that they met the following inclusion criteria: were 18 years of age or older, had an SCI requiring the use of a manual wheelchair, were considered not previously trained in wheelchair propulsion biomechanics, self-reported as being novice wheelchair users, and were able to self-propel a manual wheelchair. Participants also were required to provide informed consent. People were excluded from the study if they maneuvered their wheelchair with their lower extremities or with only one arm. Participants were compensated for their time and effort. The project was approved by an institutional review board.

Procedure

A repeated measures within-subject design was used with participants acting as their own controls. Each participant completed a demographic survey during the

Table 1 Demographics of manual wheelchair users (N = 6)

Age, mean (standard deviation)	Average in years	38 (± 17.5)
	Range, years	20–69
Sex, n (%)	Male	4 (67)
	Female	2 (33)
Race/ethnicity, n (%)	White	3 (50)
	African American	2 (33)
	Hispanic	1 (17)
Time since injury, mean (standard deviation)	Average in months	15.3 (± 10.9)
	Range, months	6–36
Level of injury, n (%)	Cervical	2 (33)
	Thoracic	4 (67)
ASIA score, n (%)	A	2 (33)
	B	2 (33)
	C	2 (33)
Receiving outpatient therapy, n (%)	Yes	3 (50)
	No	3 (50)

first assessment. Two baseline measurements (Pretest 1 and Pretest 2) were taken three weeks apart and were followed by a nine-session intervention (wheelchair training program), then the Posttest. Two pretests were used to establish a baseline of wheelchair propulsion biomechanics and skills for each participant prior to his or her participation in the wheelchair training program. All assessment and training sessions took place in a community-based research facility. At each testing session (Pretest 1, Pretest 2, and Posttest), kinematics related to propulsion and wheelchair performance overground were measured. Kinetic propulsion variables and wheelchair skills were measured immediately before the intervention (Pretest 2) and immediately after (Posttest). Participants completed the nine-session training program over a timeframe of three to five weeks, completing two or three sessions per week.

Outcome measures

Propulsion kinematics

A Video Motion Capture (VMC) system was used to collect kinematic data during propulsion. The VMC system,²⁶ consisting of eight cameras, was positioned to capture the movement of reflective markers placed on the anatomical landmark of the participant's third metacarpal and on the wheel axle of the participant's wheelchair as the participant propelled across the floor. The participant performed practice pushes across the 12-meter laboratory, and then three trials were recorded. The VMC recorded the motion as the participant propelled through the capture volume. By the time the participant entered the capture volume, he or she was propelling at a constant, self-selected normal speed.²⁷

To quantify the motion of the participant's propulsion pattern, several variables were calculated (Figure 1). Each variable was calculated for the right arm and averaged across three pushes. Sagittal plane numerical data for the third metacarpal marker on the right hand were calculated relative to the marker placed on the axle of the right wheel. The propulsion phase was determined by when the hand moved in a forward direction, measuring when the participant's third metacarpal was the same distance from the wheel axle as the wheel radius, indicating that the hand was in contact with the pushrim of the wheel.²⁸ Recovery phase was considered when the hand was not in contact with the pushrim and was not moving forward.

Three variables—area of the push loop, hand-axle relationship, and push angle—were compared across the three assessments. These three variables correspond to the recommendations outlined in the CPG (i.e. use of

Figure 1 Right hand push loop measurements designated by 3rd metacarpal.

a semicircular propulsion pattern [area of push loop], bringing the hand down toward the axle during recovery [hand-axle relationship], and longer push strokes [push angle]).⁹ The area of the push loop (total area [cm²]) represented the area made by the hand during the push and recovery phase. A positive value for area of the loop indicated that the push loop was below the pushrim, and a negative value indicated that the area of the push loop during recovery was above the pushrim.²⁷ The hand-axle relationship was measured during the recovery phase and was defined as the distance of the third metacarpal from the axle at the closest point. Push angle was defined as the angle, in degrees, between the points at which the hand contacted the pushrim and left the pushrim.²⁹ In addition, we classified the propulsion patterns found during all three assessments across all three trials of the VMC data according to four propulsion patterns described in the literature.^{1,27} The semicircular and double loop pattern most closely represent the CPG because the hand moves down toward the direction of the wheel axle during the recovery phase of these two propulsion patterns.

Propulsion performance

The Wheelchair Propulsion Test (WPT) was used to measure push frequency and effectiveness while pushing overground over a smooth, flat surface.¹² The WPT also allows for observation and quantification of

a participant's propulsion pattern. Participants were asked to propel 10 meters across a smooth, flat surface at a self-selected comfortable pace during Pretest 1, Pretest 2, and Posttest. A member of the research staff used a stopwatch to time how long it took each participant to propel across 10 meters and observed the propulsion pattern of the participant's right arm. The number of seconds (time) and the number of propulsive cycles were recorded. The research staff member also answered two yes-or-no questions about the participant's hand placement during the push and recovery phases: (1) during the contact phases, did the participant generally begin contact between the hands and the pushrims behind the top dead-center of the wheel? and (2) during the recovery phases, did the participant generally use a path of the hands that was predominantly beneath the pushrims?³⁶ Variables calculated were initial contact (yes or no), a recovery path predominantly below the pushrim (yes or no), time to complete the 10 meters (seconds), the number of pushes needed to complete the 10 meters, speed (meters per second), push frequency (cycles per second), and push effectiveness (meters per cycle). The data collected from the WPT helped identify changes of propulsion performance pre- and post-intervention and how those changes related to the CPG of minimizing the frequency of push cycles while retaining the same speed.¹²

Propulsion kinetics

The WheelMill System (WMS) is a computer-controlled wheelchair dynamometer roller system that has the ability to measure kinetic propulsion variables.³⁰ The WMS measures the forces at the wheel-roller interface. A force from the WMS that is representative of the tangential force (F_t) was calculated from the motor control signal controlling the torque of the rollers.³⁰ During Pretest 2 and Posttest, participants pushed for 30 seconds at a self-selected normal speed on the WMS. Peak force (the greatest amount of force [measured in Newtons]) and average force (measured in Newtons) were calculated across five pushes at a steady state. In addition, the slope of the smoothed calculated tangential force (Newtons per second) was calculated by taking a three-point differentiation of the signal. A five-point moving average was used to smooth the signal. The local maximum slope for each of the five pushes was found, and these values were averaged across five pushes for each assessment (Pretest 2 and Posttest). The slope of the force was calculated to determine whether the load of force the participant applied to the pushrim changed post-training. The force variables (average force, peak force, and slope of the force) were

used to identify whether the CPG of minimizing forces was met post-training.⁹

Wheelchair skills

The Wheelchair Skills Test (WST) version 4.2 was used to examine the participant's ability to safely complete wheelchair skills (e.g. propelling up and down ramps of varying slopes, turning in tight areas, maneuvering over curbs or obstacles of varying heights) in a controlled environment.³¹ The community research facility contains an indoor mobility skills course with obstacles that participants may encounter in the community (e.g. ramps, cross slopes, and curbs of varying heights). Participants performed a series of tasks on the course and were scored on their completion of each task. Tasks were performed in order of difficulty. If a participant could not complete certain tasks, he or she was not asked to complete all tasks; for example, if a participant could not maneuver over a threshold-height obstacle, the participant was not tested on the different curb heights. A spotter strap was attached to the wheelchair in case the research team needed to intervene in an unsafe situation. A member of the research team scored each individual skill on a scale of 0 to 2, with 0 indicating that the skill was not completed, 1 indicating that the skill was completed with difficulty, and 2 indicating that the skill was completed without difficulty.³¹ A wheelchair skill completion score ($[\text{sum of scores} / (\text{total number of skills} - \text{total number of skills not completed}) \times 2] \times 100\%$) was calculated and compared across Pretest 2 and Posttest to identify changes in wheelchair skills.

Wheelchair training intervention

The training program was developed from current training methods and the best available evidence. The CPG recommend minimizing the force and frequency of pushes and using long strokes during propulsion.^{2,9} The training program for manual wheelchair users was based on motor learning principles using a repetition-based approach to produce an effective propulsion technique and to prevent chronic overuse injuries that limit independence for persons with an SCI.^{23,32–35} During the training sessions, participants received verbal feedback and were able to see themselves in mirrors placed to their left side and directly in front of them.

The training program included nine 90-minute training sessions; training sessions were conducted two or three times per week. While increasing the number of practice repetitions is the emphasized component of motor learning in this study, other motor learning components that may affect skill performance and

Table 2 Training session outline

Time (min.)	Training
0:00–15:00	Check in, intro to training, review of last session
15:00–25:00	Propulsion A or B (250–350 reps)
25:00–45:00	Wheelchair skill practice
45:00–50:00	Break
50:00–60:00	Propulsion A or B (250–350 reps)
60:00–80:00	Wheelchair skill practice
80:00–90:00	Wrap up, schedule next session

acquisition were also implemented.¹⁹ For example, each session was organized to limit the number of variables presented to the participant at one time.^{36,37} Each training session included two propulsion practice sets and two opportunities to practice other wheelchair skills (Table 2). The training sessions were led by two occupational therapists with assistive technology professional certifications who have clinical experience with wheelchair evaluations and training.

The primary focus of the training was propulsion biomechanics. Propulsion training was divided into two propulsion sets. Propulsion Set A focused on using longer push strokes. Propulsion Set B focused on dropping the hand down toward the axle. The two propulsion sets were randomized throughout training to maximize random practice. Participants were coached and cued throughout each session in order to correct propulsion form and provide extrinsic post-responsive information on propulsion movements. At the beginning of the training program, more verbal cues were used; as the sessions progressed, the number of cues decreased.³⁸ The trainer emphasized the participant's ability to self-identify when he or she needed to make a correction, having participants look in a mirror during their practice repetitions. All propulsion sets were completed on the WMS, and participants achieved 500–700 repetitions per session. Documentation in the research literature indicates that 300–800 repetitions per session turn a movement into a learned skill.³⁹ After every three sessions, the number of repetitions per session increased (Sessions 1–3: 500 repetitions, Sessions 4–6: 600 repetitions, Sessions 7–9: 700 repetitions). Each participant completed 5400 repetitions by the end of the training program. After each propulsion set, the participant was taken off the WMS, and the principles taught on the WMS were encouraged overground. However, the counted practice repetitions all occurred on the WMS.

The secondary goal of the training program was improvement of wheelchair skills. The wheelchair skills introduced during each session were used to vary the practice schedules of movement, provide an external

focus of attention, and further educate participants on valuable wheelchair skills. An earlier qualitative study identified important wheelchair skills for new manual wheelchair users to learn. The skills taught during the two 20-minute segments of each session were taken from the results of this study.⁴⁰ These wheelchair skills included basic wheelchair maintenance, backward propulsion, maneuvering tight spaces, opening and closing doors, going up and down ramps, pushing across a cross slope, going over curbs and bumps, and performing a wheelie. These skills represent 20 of the 32 skills tested on the WST (Table 3). One skill that was addressed in the wheelchair training that is not part of the WST is wheelchair maintenance. The portions of the training program that involved propulsion and maneuvering environmental obstacles were first taught on the WMS, which simulates the resistance and wheelchair position of surfaces such as ramps and cross slopes (Figure 2). The device provides an opportunity to safely train participants on propulsion techniques and obstacle manipulation while in a secure position, allowing participants to focus solely on the technique of each skill. Once these skills were introduced on the WMS, participants were transitioned onto the actual surfaces for additional training to introduce navigation of obstacles in the lived environment.⁴¹ The additional training included pushing up and down ramps of varying slopes and pushing over different surfaces (carpet, tile, gravel) using the techniques taught on the WMS. These ramps and surfaces were all located in and around the testing facility.

Data analysis

Customized Microsoft Excel spreadsheets were used to process all project data.⁴² VMC data were tracked and edited using motion analysis software (Cortex 2.1, 2010). We used SPSS version 21 on a Windows-based computer for data analysis.⁴³ A repeated measures analysis of variance (ANOVA) was used to determine whether there were significant differences in the wheelchair kinematic variables and the wheelchair performance variables across three testing times ($P < 0.05$). Mauchly's test of sphericity was used to test whether the assumption of sphericity was met. For the repeated measures ANOVA results, the assumption of sphericity was met ($P > 0.05$) for all variables. The Bonferroni *post hoc* tests were used to determine which assessments differed from one another. A paired *t*-test was used to determine significant differences in the wheelchair push force variables (WMS) and wheelchair skills (WST) variables between Pretest 2 and Posttest ($P < 0.05$). Effect sizes (r) were calculated to determine

Table 3 Wheelchair skills taught during the training

Item #	Wheelchair Skills Test Items	Wheelchair Skills Included in Training
1	Rolls forwards (10 m)	x
2	Rolls backwards (2 m)	x
3	Turns while moving forwards (90 degrees)	x
4	Turns while moving forwards (90 degrees)	x
5	Turns in place (180 degrees)	
6	Maneuvers sideways (0.5 m)	x
7	Gets through hinged door	x
8	Reaches high object (1.5 m)	
9	Picks object up from floor	x
10	Relieves weight from buttocks (3 sec)	
11	Transfers to and from bench	x
12	Folds and unfolds wheelchair	x
13	Rolls 100 m	x
14	Avoids moving obstacles	
15	Ascends 5 degree incline	x
16	Descends 5 degrees incline	x
17	Ascends 10 degree incline	x
18	Descends 10 degree incline	x
19	Rolls across side-slope (5 degree)	x
20	Rolls on soft surface (2 m)	x
21	Gets over gap (15 cm)	
22	Gets over threshold (2 cm)	x
23	Ascends low curb (5 cm)	x
24	Descends low curb (5 cm)	x
25	Ascends curb (15 cm)	
26	Descends curb (15 cm)	
27	Performs stationary wheelie (30 sec)	x
28	Turns in place in wheelie position (180 degrees)	
29	Descends 10 degree incline in wheelie position	
30	Descends curb in wheelie position (15 cm)	
31	Gets from ground into wheelchair	
32	Descends stairs	

the magnitude of differences before (Pretest 2) and after wheelchair training (Posttest). Effect sizes are defined as small ($r = 0.10\text{--}0.29$), medium, ($r = 0.30\text{--}0.49$), or large

($r > 0.50$).⁴⁴ Individual results were also reported to identify inter-variability and intra-variability across participants and assessments.

Figure 2 Cross slope practice.

Results

Ten participants were screened. Two persons did not meet the eligibility criteria, and two did not attend all assessment and training sessions due to transportation and health issues. Six participants completed the three assessments and each of the nine training sessions. Below are group comparison results and overall trends of individual results.

Group comparison

Propulsion kinematics

Two of the three wheelchair push kinematics variables collected by the VMC system were found to be significant (Table 4). The wheelchair training intervention elicited significant changes in the area of the push loop ($F(2, 10) = 9.8$), with the area remaining consistent between the two pretest measurements and increasing post-intervention (see Table 4). The area was a positive value, indicating that the hand motion during recovery was below the pushrim (or toward the wheelchair axle). *Post hoc* analysis revealed that the area of the push loop significantly increased ($P = 0.05$) from Pretest 2 to Posttest, with a mean difference of 309.7 cm² (95% CI, 5.7 to 613.6). The wheelchair training intervention also elicited significant changes in the hand-axle relationship pre- and post-intervention ($F(2, 10) = 5.2$), with the distance between the third metacarpal and the wheel axle decreasing during recovery between the pretest and posttest assessments. To put this into perspective, if a participant's wheel is 60 cm (24 inches) in diameter with a pushrim diameter of about 56 cm, the radius maximum would be about 28 cm if the hand was at or below the level of the pushrim during the recovery phase of the push. The Pretest values of 26.1 cm and 27.1 cm indicate that the

hand was close to the pushrim during the recovery phase. After the intervention, that hand moved closer to the axle, with the hand-axle relationship being 19.3 cm. *Post hoc* analysis showed no significant changes between each of the assessment points. The wheelchair training intervention did not elicit significant changes in push angle pre- and post-intervention ($F(2, 10) = 3.6$), with the push angle increasing during the push phase between the pretest and posttest assessments. However, push angle did not increase for all participants. The three wheelchair push kinematic variables had a medium-to-large effect size from Pretest 2 to Posttest (see Table 3).

Propulsion performance

The recovery item on the WPT (defined as bringing the hand below the pushrim toward the axle during the recovery phase of the push cycle) was found to be significant (see Table 4). Prior to the wheelchair training program, only one participant brought his hand below the pushrim toward the axle during the recovery phase of the push cycle. After training, all but one participant brought their hands below their pushrims during the recovery phase. The wheelchair training intervention elicited significant changes in the speed (meters per second) to push the 10 meters ($F(2, 10) = 11.39$). *Post hoc* analysis revealed that the speed across 10 meters significantly increased from Pretest 2 to Posttest, with a mean difference of 0.16 meters per second (95% CI, 0.24 to 0.10). The wheelchair training intervention elicited significant changes in the push effectiveness (meters per push) across the 10 meters ($F(2, 10) = 4.33$). *Post hoc* analysis showed no significant changes between each of the assessment points. The wheelchair training intervention did not elicit significant changes

Table 4 Wheelchair training intervention results

Wheelchair kinematics (VMC)	Pretest 1	Pretest 2	Posttest	P value	Effect Size (r)
Area of the loop (cm ²)* ⁺	34.8(191.8)	27.0(227.1)	336.6(247.5)	<0.01	0.55
Hand-axle relationship (cm)*	26.1(5.1)	27.1(4.5)	19.3(7.3)	0.03	0.54
Push angle (degrees)	76.8(11.3)	76.1(8.0)	85.6(11.2)	0.07	0.44
Wheelchair performance (WPT)					
Contact (yes or no)	0.8(0.4)	0.8(0.4)	1.00(0.00)	0.40	0.33
Recovery (yes or no)*	0.2(0.4)	0.2(0.4)	0.8(0.4)	<0.01	0.60
Speed (m/s)* ⁺	0.98(0.24)	0.90(0.18)	1.07(0.19)	<0.01	0.42
Push effectiveness (m/cycle)*	0.96(0.21)	0.95(0.21)	1.12(0.24)	0.04	0.35
Push frequency (cycles/s)	1.02(0.20)	0.96(0.1)	0.96(0.06)	0.65	0
Wheelchair push forces (WMS)					
Average force (N)	—	10.9(4.5)	8.0(4.3)	0.10	0.31
Peak force (N)	—	20.6(8.6)	16.4(8.4)	0.13	0.24
Slope of the force (N/s)*	—	149.1(72.1)	114.8(56.6)	0.03	0.26
Wheelchair skills (WST)					
Skill completion score (%)	—	67.1(23.2)	73.5(18.0)	0.08	0.15

Note: Mean score (standard deviation); * $P < 0.05$; ⁺*Post hoc* analysis significant between Pretest 2 and Posttest.

in push frequency (pushes per second) before and after intervention ($F(2, 10) = 0.45$). The push contact item of the WPT (defined as a long push stroke achieved by reaching back before the top dead-center of the wheel to initiate a push) was not significant ($P = 0.40$). All but one participant in the pretest assessments initiated his or her push before the top dead-center of the wheel. After the wheelchair training intervention, all participants initiated pushes behind the top dead-center of the wheel. The contact, recovery, speed, and push effectiveness variables had a medium-to-large effect size from Pretest 2 to Posttest (see Table 3).

Propulsion kinetics and wheelchair skills

The slope of the force elicited a significant decrease of 34.3 N/s (95% CI, 5.2 to 63.4) post-intervention (Table 4). Participants' forces (average and peak) decreased after the wheelchair training intervention (Table 4). However, no significant difference was found for average force or peak force in the paired t-test results. Wheelchair skills as measured by the WST also showed no significant difference (Table 4). All participants' wheelchair skills scores increased from Pretest 2 to Posttest; two participants had increases of approximately 14 to 17%, and two participants already had high scores (i.e. 90% and 94%) before starting the training (Figure 3). Force variables and the wheelchair skills score variables had a small effect size from Pretest 2 to Posttest (Table 3).

Individual results

Three distinct groupings of kinematic results emerged among the participants: (1) changes in all three of the kinematic variables (i.e. area of the push loop, hand-axle relationship, and push angle) pre-and post-intervention, (2) changes in at least one kinematic variable, and (3) consistent variables across each assessment. Each of these groupings is described below in detail.

Figure 3 Wheelchair skills test scores.

Two participants made kinematic changes in all three propulsion variables. Participant 1 (female, thoracic-level injury) increased the area of the push loop and push angle and decreased the distance from her hand marker to the wheel axle during the push recovery phase (Figure 4). She changed her propulsion pattern to a semicircular one, with her hand moving toward the axle during the recovery phase (Table 5). Participant 1 also increased her speed and push frequency during the 10-meter test and decreased her average force, max peak force, and slope of force pre- and post-intervention. However, her wheelchair skills scores only slightly increased (by 3%) after the wheelchair training intervention.

Three participants made changes in at least one of the kinematic variables (example, Participant 2). For example, Participant 2 (female, cervical-level injury) changed her propulsion pattern post-intervention to a semicircular pattern. She also increased her speed and push frequency during the 10-meter test, but she did not have any changes in force pre- and post-intervention. Her wheelchair skills score increased by almost 17%.

Participant 4 (male, thoracic-level injury) displayed biomechanics as described by the CPG both pre- and post-intervention. He increased the area of his push

Pretest 1: Area: -10.7cm², Angle: 74.9°, Hand-Axle: 27.9cm, PP: +AR
 Pretest 2: Area: 9.4cm², Angle: 78.2°, Hand-Axle: 29.8cm, PP: +AR
 Posttest: Area: 711.3cm², Angle: 104.5°, Hand-Axle: 11.8cm, PP: SC

Figure 4 Participant 1: Wheelchair push kinematic measurements.

Table 5 Propulsion patterns pre- and post-training

Participant	Pre1T1	Pre1T2	Pre1T3	Pre2T1	Pre2T2	Pre2T3	PostT1	PostT2	PostT3
1	+AR	+AR	+AR	+AR	+AR	+AR	SC	SC	SC
2	~+AR	+AR	+AR	~+AR	~+AR	~+SL	~DL	~DL	~DL
3	~+SL	~+SL	~+SL	~+AR	~+AR	~+AR	DL	DL	DL
4	DL	DL	DL	DL	DL	DL	SC	SC	SC
5	+SL	DL	DL	+SL	+SL	+SL	~DL	~SC	SC
6	~+SL	~+SL	~+SL	+SL	~+AR	~+SL	~+AR	~SC	~SC

Pre = Pretest 1, Pre2 = Pretest 2, Post = Posttest T = trial; DL = double loop over pattern, SC = semicircular pattern, AR = arc pattern, SL = single loop over pattern; + = hand did not drop below pushrim during recovery; ~ = inexact pattern match.

loop post-intervention. This participant changed from a double loop pattern to a semicircular pattern post-intervention. His wheelchair push performance (WPT) remained consistent before and after intervention. His force values decreased after the intervention. He had a high wheelchair skill completion score on the WST pre-intervention and, therefore, experienced no change in the score post-intervention.

Discussion

The primary purpose of this investigation was to pilot-test a training program for new manual wheelchair users with SCI. We found indications of changes in propulsion that follow the recommended CPG.⁹ All six participants made changes related to the CPG. Some participants made changes across all variables and others just a few of the variables. The significant results from the area of the push loop and the hand-to-axle relationship (from the VMC data) and the recovery item (on the WPT) indicate changes in the propulsion patterns, with participants bringing their hands down toward the axles of their wheelchairs. This was further indicated by classification of propulsion patterns exhibited by each participant across all assessments and trials (Table 5). The changed propulsion pattern toward a semicircular and/or double loop pattern meets part of the CPG recommendations. Significant changes in push effectiveness and speed as measured by the WPT may be related to the changes in propulsion pattern. The significant decrease in the slope of the force post-intervention may indicate a decrease in the rate of loading the force onto the pushrim. The decrease in the slope of the force may be related to the direction the hands approach the pushrim after an arc recovery pattern as compared to semicircular recovery pattern. A few of the reasons push angle and average and peak forces were not significant include wheelchair positioning issues, variability in injury level, one participant having good biomechanics to start, and some participant inconsistencies across assessments and training. Even though these variables were not significant, changes were made across

participants, with two participants making dramatic changes in each of these variables.

The secondary purpose of the study was to identify whether the person's ability to complete wheelchair skills independently and safely improved after receiving the training. No significant difference was found in wheelchair skill proficiency before and after the wheelchair training intervention. Several reasons for this could be attributed to a ceiling effect (two participants started the intervention with high scores), the fact that only 20 out of the 32 items on the WST were addressed during training, and that some of the advanced skills (e.g. wheelies) may require more training time than was allotted.

Manual wheelchair training studies often use able-bodied participants to study the impact of training on new manual wheelchair users^{24,45} or use experienced wheelchair users.^{16,17} We intentionally chose the recruitment criteria to include new manual wheelchair users in order to better understand the factors involved with training this population. For example, wheelchair positioning may not have much of an impact on propulsion biomechanics for an able-bodied person, and more experienced users may be positioned more optimally for propulsion. Wheelchair positioning is not always optimal for proper biomechanics for new wheelchair users receiving their first wheelchair, with common issues being maneuverability and use of the wheelchair across environments.⁴⁶ Some participants in this study experienced wheelchair positioning that prevented them from fully implementing the training recommendations. One participant was seated high in the wheelchair to make transfers into and out of the wheelchair easier, but this made it difficult for her to drop her hands toward the axle during the recovery phase of her push. However, she did increase her push angle and overall wheelchair performance overground. Previous studies have addressed some of the pain and chronic overuse injuries of manual wheelchair users by modifying the wheelchair and the person's position relative to the wheelchair.⁴⁷ Results suggest that wheelchair

seating and positioning have an impact on biomechanics and wheelchair skills.

The results of this project are similar to those found in previous wheelchair training research. Studies using components of motor learning, such as visual feedback, found subtle changes in propulsion biomechanics, including longer slow push patterns similar to the changes found in this study.^{15,17,48,49} Across studies, variables associated with push forces have varied in response to wheelchair propulsion interventions, including decrease in push force, increase in push force, and no change in push force.^{16,17,49} We did not find significant change related to average or peak force but did find change in the slope of the force. The WPT results found in this study were similar to results reported in a previous study with new wheelchair users.¹² The main focus of this study was wheelchair propulsion biomechanics, with a secondary emphasis on wheelchair skills. Although there was some indication of change in wheelchair skills (7% increase), the results were not significant. Studies solely focused on wheelchair skills have shown significant changes, with increases up to 25% in wheelchair skills scores on the WST post-intervention.¹⁴

The wheelchair training intervention described in this paper included wheelchair propulsion training and wheelchair skills training. Other interventions tend to focus on teaching either propulsion techniques or wheelchair skills. The duration of our wheelchair training intervention included nine 90-minute sessions. Other wheelchair training interventions reported in the literature ranged from one visit to seven weeks consisting of two or three visits per week.^{49,50} Studies using exercise and motor learning approaches were longer in duration.^{17,50} The number of sessions and the amount of time per session for this study were necessary for the repetition-based approach and focused on turning proper biomechanics into a learned motion. Each session consisted of 500 to 700 total practice repetitions for a total of 5,400 repetitions by each participant at the completion of the intervention. The number of practice propulsion repetitions during rehabilitation for manual wheelchair users with SCI is unclear. Recommendations of 300 to 800 practice repetitions per session for skill acquisition have been documented in the neurorehabilitation literature.³⁹ The number of practice repetitions offered in this study falls within that range. All participants tolerated and completed the number of repetitions per session.

This is one of few manual wheelchair training studies to use components of motor learning and to provide instruction-based interventions with relatively new manual wheelchair users with SCI. This study confirms

the importance of wheelchair seating and positioning in conjunction with wheelchair training. The CPG provide recommendations based on research for clinicians to follow when teaching wheelchair propulsion biomechanics but no information on how to teach these recommendations. A validated wheelchair training protocol, the Wheelchair Skills Training Program (WSTP), provides an approach to teaching wheelchair biomechanics and background on motor learning, stating the importance of practice but indicating that the specific amount of practice varies.^{14,51,52} Furthermore, clinicians report that they rarely use validated protocols when teaching wheelchair skills during rehabilitation.²⁵ The results of this study indicate that new manual wheelchair users can tolerate up to 700 practice propulsion repetitions per session and that approximately 5000 repetitions contribute to changes in propulsion patterns. This instruction was provided by a clinician and did not require a computer system with feedback. More research is needed to understand “dosing,” or the number of repetitions needed to promote the propulsion techniques described in the CPG. As rehabilitation advances, it is important that clinicians use evidence-based practices such as training programs based on motor learning principles.⁵³

This study had many limitations, including a small sample size and heterogeneity (length of injury and level of injury) of the participants recruited. The small sample size and range in length of injury were the result of difficulty recruiting new manual wheelchair users; in part, this was because of difficulty recruiting participants who were medically stable and emotionally ready to work on wheelchair skills and because of lack of resources to support transportation to and from the training sessions for potential participants.^{25,54} Duration of injury did not always equate to duration of wheelchair use. For example, the participant who had been injured for 36 months reported not independently using her manual wheelchair since she received it. She relied on her daughter to push her wheelchair for her. Even though she was 36 months post-injury, she was a new independent manual wheelchair user when she entered the training program. This study had a small sample design, with participants serving as their own controls, which can be useful for evaluating changes following an intervention, especially when participants have significant individual variability.^{55,56} However, an experimental design with a larger sample size, random selection, and a control group would permit the use of a more powerful statistical approach. A methodological limitation of the study was that the kinematic data and kinetic (force) data were collected

on different surfaces. The force data were collected on a wheelchair roller system, so the force data may not be representative of overground propulsion. Future research is needed to further test repetition-based wheelchair training with a more rigorous research design, to measure kinematics and kinetics at the same time overground, and to examine the retention of propulsion biomechanics and skills after the training sessions. Additionally, other factors involved in motor learning, the rate at which new wheelchair users learn, and the involvement of depression, motivation, and cognitive processing in the motor learning process should be evaluated in relation to the training program. Future studies should include a review of wheelchair positioning and allow for adjustments prior to the training. In conjunction with wheelchair seating setup, practicing the proper push biomechanics through repetition-based training may promote the use of the recommended and researched biomechanics.

Conclusion

This project identified trends in change related to a repetition-based motor learning approach for propelling a manual wheelchair. The changes found were related to the propulsion pattern of the participants. Participants post-training changed the direction of their hands during the recovery phase of each push, bringing their hands below the pushrim. Studying manual wheelchair use with new manual wheelchair users has potential for change and preventing or reducing pain and chronic overuse injuries. Participants were able to tolerate 500 to 700 propulsion repetitions during each training session. However, there were many challenges with the implementation of this intervention with new manual wheelchair users, including recruitment. The results of this study have clinical implications, as the motor learning principles used in the training program developed during this research could be applied to wheelchair skills training during rehabilitation.

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