Training Youth With SCI to Improve Efficiency and Biomechanics of Wheelchair Propulsion: A Pilot Study

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Background: Long-term manual wheelchair users are at an increased risk of developing upper extremity (UE) joint pain and injuries due to the repetitive nature of wheelchair propulsion. Youth who sustain spinal cord injuries (SCIs) may be at even greater risk due to the many years they may be wheelchair dependent. There has been a decreasing trend in duration of initial rehabilitation, therefore little time is spent on training of proper wheelchair propulsion. An objective evaluation along with proper training may help prevent the risk of UE pain and injuries over time. **Objective:** To develop a training program to improve the efficiency and biomechanics of wheelchair propulsion in youth with SCI and evaluate changes made following propulsive training. **Methods:** Manual wheelchair users between 4 and 21 years old with SCI were recruited from one hospital. Demographic and clinical measures were collected and the subjects completed the Wheelchair User's Shoulder Pain Index. SmartWheel metrics were collected at baseline and following propulsive training on a roller system. Analyses assessed differences in SmartWheel metrics pre and post training. **Results:** The 23 participants were between 7 and 19 years of age; 57% were male and 69% with paraplegia. Significant improvements were found for SmartWheel metrics of peak backwards force that improved from $-3.08 \text{ Newtons (N)} \pm 2.1$ pre training to $-2.37 \text{ N} \pm 1.9$ ($p = .041$) post training and for push mechanical effectiveness that improved from $.575 \pm .14$ at baseline to $.631 \pm .17$ post training ($p = .033$). **Conclusion:** Our results suggest that an objective wheelchair assessment and propulsive training may be a valuable tool for youth with SCI. **Key words:** *pediatrics, spinal cord injury, wheelchair propulsion*

Among youth with spinal cord injury (SCI), wheelchair mobility is fundamental in supporting activities, participation, and quality of life. The use of wheelchairs provides children and adolescents greater independence and the ability to participate in higher level functional activities.¹ It is well documented that such participation and engagement has a positive impact on social well-being, physical fitness, and overall quality of life.^{2,3} An unfortunate drawback to long-term manual wheelchair use is an increased risk of upper extremity (UE) joint pain and injury, which may be due to improper propulsion techniques and the repetitive nature of these movements.⁴⁻⁷ Shoulder pain is reported by 52% of adults with pediatric-onset SCI including 51% of those with paraplegia.^{1,8} This is comparable to the prevalence (30%-60%) of shoulder pain in individuals with adult-onset SCI.⁹⁻¹¹ The high prevalence of UE pain in adults with pediatric-onset SCI highlights

the need for measures that preserve UE function and reduce the risk of shoulder injuries. Hwang et al reported that the likelihood of UE joint pain in adults with pediatric-onset SCI increases over time with injury duration regardless of injury severity in the same population.¹² Furthermore, in adults with pediatric onset SCI, shoulder pain is associated with decreased participation, employment, and life satisfaction.⁸

Over the past few decades, duration of initial inpatient rehabilitation and funding for secondary intensive rehabilitation have decreased. This most likely limits the training on proper propulsion techniques and ways to reduce the risk of future injuries on the UEs.¹³ Since the number of youth using manual wheelchairs is significant, there remains a critical need to understand how to objectively study wheelchair propulsion and train wheelchair users to reduce the risk of UE injury over their lifespan.

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A clinical practice guideline published in 2005 by the Consortium of Spinal Cord Medicine makes specific recommendations in regard to wheelchair propulsion including routine evaluations of wheelchair propulsion techniques. The recommendations include minimizing the frequency of repetitive upper limb tasks, minimizing forces required to complete upper limb tasks, and using long, smooth strokes during propulsion that limit high impact on the push rim. Four different patterns of recovery have been identified in wheelchair propulsion including arc, semi-circular, single-looping over, and double-looping over. Additionally, the Consortium of Spinal Cord Medicine recommends that the hand drift down naturally after rim release, keeping it below the push rim when not in actual contact with it.¹⁴ The semicircular pattern of propulsion, which is one of the patterns that arises when the user's hand drops below the push rim in the recovery phase of propulsion, has been shown to be the preferred pattern in manual wheelchair propulsion in multiple studies.¹⁵

The SmartWheel is a tool utilized to measure kinetics and the forces acting on the UE joints. The SmartWheel can be mounted to most wheelchairs and can calculate and record forces applied to the push rim during propulsion via force transducers and wirelessly transmit

that data to a computer. The data are used to generate a report that summarizes the efficiency and biomechanics of the user's wheelchair propulsion and can provide the user feedback for training. SmartWheel metrics include peak force, peak backwards force, speed, push length, push frequency, peak/average force ratio, average push force, and push mechanical effectiveness (Table 1).¹⁶ The SmartWheel, used in conjunction with a 3-D motion capture system, can provide a comprehensive analysis of UE joint motion, joint forces, and temporal/spatial parameters during wheelchair propulsion.^{16,17}

Multiple studies have evaluated the use of feedback in manual wheelchair users to assess its usefulness in improving measures of wheelchair propulsion with mixed results.¹⁸⁻²¹ De Groot et al and Kotajarvi et al both evaluated the use of visual feedback in improving fraction of effective force (FEF) during wheelchair propulsion. These studies had mixed results with subjects either not improving in FEF or improving FEF at the cost of mechanical efficiency.^{18,20} Another study utilized both visual and verbal feedback and succeeded in improving both contact angle and cadence during propulsion but with a higher peak force.¹⁹

Because these studies involved adults, the purpose of this pilot project was to develop a training paradigm that would evaluate and improve

Table 1. SmartWheel parameters

Parameter	Definition
Peak force	For each steady-state push, the peak force is measured.
Peak backwards force	This is average peak backwards force of all the steady-state pushes and shows the extent to which the client is unintentionally applying the wheelchair brakes with each push. The parameter is only valid when the participant is not actually trying to brake.
Speed	This is the average speed of the SmartWheel during steady state. (The time after the first three pushes.)
Push length	This is the average length of the participant's push, in degrees.
Push frequency	This is how many times per second, on average, the participant pushes on the SmartWheel.
Peak/average force ratio	This is the ratio between the peak force during a push and the average force during a push. It is averaged across all steady-state pushes. It provides an indication of how smoothly pushes are applied to the SmartWheel's hand-rim. A lower ratio indicates the peak force is closer to the average force, which can indicate a smoother push.
Average push force	This is the average force the subject applies to the SmartWheel's hand-rim averaged over all steady-state pushes.
Push mechanical effectiveness	This indicates the approximate percentage of applied force that is directed such that the wheelchair is accelerated. For example, if much of the applied force is downward or outward, this value will be lower, because pushing inwards toward the hub or pushing outward does not contribute to wheelchair acceleration. The parameter is intended to provide a "red flag" for abnormally inefficient push mechanics.

the efficiency and biomechanics of wheelchair propulsion in youth with SCI by integrating real-time feedback from the SmartWheel pre and post training. In addition, both a physical therapist and a biomedical engineer were present and provided feedback to the subjects following observational assessment of propulsion pattern. Our hypothesis was that propulsive training with real-time visual and verbal feedback would result in improved biomechanical measures during straight-line propulsion over a tile floor.

Methods

Participants

Participants were identified and recruited from one pediatric specialty hospital. Inclusion criteria included youth 4 to 21 years of age who were manual wheelchair users and who had sustained an SCI at least 3 months prior to participation in this pilot study. Subjects with concomitant or preexisting traumatic brain injuries were excluded. The study protocol, consent, assent, and Health Insurance Portability and Accountability Act forms were all reviewed and approved by the Institutional Review Board. Informed consent and assent when appropriate were obtained from all participants and their caregivers as appropriate, and the ethical treatment of human subjects was followed throughout the research process.

Data collection

Demographic information was collected from the medical records for all participants including gender, height, weight, age, level of injury, age at time of injury, amount of time in months the participant had been using a manual wheelchair, and handedness. The subjects then completed the Wheelchair User's Shoulder Pain Index (WUSPI) questionnaire to determine preexisting UE pain.

The subjects were studied in a 3-D motion analysis laboratory where reflective markers were placed on their UEs on the acromion process, humerus, medial and lateral epicondyles of the elbow, the styloid process of the radius and ulna, and the third metacarpophalangeal joint (MCP) and on the axle of each wheel (**Figure 1**).

Each participant's wheelchair was fit with the appropriate size SmartWheel (22 in. to 26 in.), which was placed on the subject's chair on the dominant hand side. Additionally, an exact size matched wheel, provided by the manufacturer, was placed on the opposite side to equal the weight and inertia of the SmartWheel. After placement of both wheels, we collected four trials of baseline data by having the subjects propel their chairs across an approximately 50-foot tile floor. The only instructions given were to go down to the other side of the room at your normal speed. Feedback was provided to the subjects utilizing observational information by a physical therapist and a biomedical engineer on push mechanics and the self-selected shape of propulsion stroke along with SmartWheel data.

Following this, the subjects watched a 2-minute demonstration video describing how the training would be conducted and education on the preferred propulsion pattern. Participants were then securely fastened to a roller system (**Figure 1**) and aligned to view a 42-in. video monitor in our 3-D Vicon motion capture lab. Hand marker trajectory was recorded using the motion capture software by tracing the shape of the propulsive stroke, and the reflective markers on their UEs allowed them to see their own propulsion patterns in real time on the monitor (**Figure 2**). Subjects were instructed to create a smooth, semicircular pattern by allowing their hand to naturally drift downward in the recovery phase. After approximately 10 minutes of training, we collected another four trials of SmartWheel data by repeating the testing across the same 50-foot tile floor.

Data analysis

The Statistical Package for the Social Sciences (IBM SPSS, version 22.0; Armonk, NY) was used to analyze the data. Descriptive statistics were used to summarize demographic data points listed above and paired samples *t* tests were used to compare measures of propulsion including peak force, peak backwards force, speed, push length, push frequency, peak/average force ratio, average push force, and push mechanical effectiveness before and after training.²² Cohen's *d* was used as a measure of effect size (ES) to assess the magnitude

Figure 1. Picture of participant showing the roller system set up and reflective marker placement on the upper extremities. Note: Subject in this photo had additional markers that were placed for a separate project.

of the difference between each pair of means, where 0.2 = small effect, 0.5 = medium effect, and 0.8 = large effect.

Results

Of the 23 participants in the study (13 males, 10 females), 69% had paraplegia and the mean age at time of participation was 11.9 years (range, 7-19). The average duration of manual wheelchair use was 43.8 months with a range of 3 to 132 months, and injury levels of participants ranged from C6 to L2. Six subjects (26.0%) exhibited shoulder pain at the time of the study, while only two (8.6%) had complaints of elbow or wrist pain.

Demographic and injury-related characteristics as listed in the data analysis were unrelated to study outcomes of interest. Analyses of the biomechanical measures of propulsion were conducted using paired samples *t* tests. Significant findings were identified for both peak backwards force and

push mechanical effectiveness. Post training, the mean peak backwards force was significantly less than the mean peak backwards force pre training, indicating improvement (-2.37 ± 1.9 vs -3.08 ± 2.1 ; $p = .041$). Additionally, the mean push mechanical effectiveness was significantly improved post training ($.631 \pm .17$ vs $.575 \pm .14$; $p = .033$), indicating that a greater percentage of the force applied by the subject contributed to acceleration of the wheelchair following training. It is also important to examine the magnitude of effect in a way that is not influenced by sample size, particularly due to the pilot nature of the current study. Consistent with the significance testing, peak backwards force and push mechanical effectiveness both demonstrated small effects according to Cohen's *d* ($d = -0.35$ and -0.36 , respectively). Further, three other pairs of means came close to demonstrating a small effect, including peak force ($d = 0.15$), push frequency ($d = 0.16$), and average push force ($d = 0.18$) (Table 2).

Figure 2. Side view of upper extremity reflective markers and hand marker trajectory using motion capture software during training.

Table 2. SmartWheel metric results pre and post training ($N = 23$)

SmartWheel metric	Pre training Mean (SD)	Post training Mean (SD)	t statistic; significance ^a	Cohen's d ^b
Peak force (N) ^c	44.35 (17.8)	41.66 (17.7)	1.22; $p = .236$	0.15
Peak backwards force (N) ^d	-3.08 (2.1)	-2.37 (1.9)	-2.17; $p = .041$	-0.35
Speed (m/s)	1.13 (.24)	1.12 (.21)	0.25; $p = .806$	0.05
Push length (deg) ^d	56.45 (14.6)	58.03 (12.5)	-0.79; $p = .434$	-0.12
Push frequency (1/s) ^c	.879 (.19)	.852 (.14)	0.69; $p = .500$	0.16
Peak/avg force ratio ^c	1.25 (.12)	1.26 (.13)	-0.21; $p = .839$	-0.08
Average push force (N) ^c	34.78 (11.9)	32.54 (12.3)	1.29; $p = .211$	0.18
Push mechanical effectiveness (%) ^d	.575 (.14)	.631 (.17)	-2.28; $p = .033$	-0.36

^aBold indicates significance at $p < .05$.

^b0.2 = small effect, 0.5 = medium effect, 0.8 = large effect.

^cLower number is preferable.

^dHigher number is preferable.

Discussion

Overuse injuries at the shoulder, elbow, and wrist that may contribute to destructive arthropathies and carpal tunnel syndromes are well documented.⁵ It has been shown that inefficient force applications and poor biomechanics may be important factors in contributing to these injuries, although most of this research has been focused on adults.²³ Previous studies have shown that lower forces, slower cadence, and circular strokes during wheelchair propulsion may assist in preventing injury.²³ Because of the relatively long lifespan of youth with SCI, they are most likely at high risk of developing UE pain and overuse injuries and would have to endure them for a longer time compared to those with adult-onset SCI. Therefore, intervention with children with SCI is imperative.

Employing an objective wheelchair assessment and proper training on an ongoing basis as the child is growing as well as when the child receives new wheelchairs may help reduce the development of UE injuries over time. In the current study, we evaluated such a program and chose to use real-time visual feedback because it has been shown to be particularly effective in improving accuracy and manual consistency in children.²⁴ In our current study and with a limited number of participants, we saw significant gains in terms of peak backwards force and push mechanical effectiveness after propulsion training using the semicircular pattern. The average peak backwards force was significantly less post training, implying that overall the subjects improved in unintentionally slowing the wheelchair down with each push, which would lead to a smoother stroke. Additionally, the improvements in push mechanical effectiveness (a parameter intended to provide a red flag for inefficient push mechanics) show that post training, a greater percentage of the applied force to the hand-rim contributed to wheelchair acceleration. Push mechanical effectiveness in the current study is an equivalent parameter as FEF in previous studies.^{18,20} Although we were able to improve push mechanical effectiveness in this study, we did not measure oxygen consumption, so it is unknown whether this improvement was at the expense of mechanical efficiency as has been found in a previous study.¹⁹

No significant statistical changes were found post training for peak force, push frequency, and average

push force. Although these metrics were mildly improved, they had very small effect sizes and we cannot conclude that any differences were related to the training intervention. Speed and peak/average force ratio remained relatively consistent post training. Future research should continue to evaluate the potential impact of similar wheelchair assessment and training programs incorporating feedback for children with SCI including serial programs as they age.

In addition to a small number of participants, there are several other limitations to this study. Wheelchair fit is an important component of proper wheelchair propulsion, and we did not evaluate or adjust the wheelchair prior to or during the training session. By evaluating subjects only in forward propulsion at a steady speed, parts of wheelchair propulsion including turning and maneuvering around obstacles were negated. Another limitation of this pilot project was the short distance of propulsion due to the constraints of the space in the motion lab. Additionally, as the training was performed on the roller system we had available to us, the resistance during propulsion on the tile floor was not the same as on the roller system. Because of the different inertia, the hand has to accelerate the wheel at the beginning of the push on the rollers, while on the ground the hand has to catch up with an already rolling wheel and attempt not to brake it. Finally, as this was a pilot study with limited resources, there was no control group, it was only a single training session, and we were unable to conduct long-term follow-up to assess carryover of training or possible effects on UE pain.

Conclusion/Implications

Wheelchair propulsion is a skill that may be quickly improved with proper education, minimal training, and practice. As current rehabilitation trends allow little time for this in the traditional setting, a comprehensive assessment of wheelchair propulsion and education on techniques to prevent future UE injury must be repeated over time and throughout the child's lifespan with the goal of improving wheelchair propulsion and reducing overuse injuries to the upper extremities.

Conflicts of Interest

The authors declare no conflicts of interest.

REFERENCES

1. Vogel LC, Zebracki K, Betz RR, Mulcahey M. *Spinal Cord Injury in the Child and Young Adult*. London: Mac Keith Press; 2014.
2. Hansen N, Forchheimer M, Tate D, Luera G. Relationships among community reintegration, coping strategies, and life satisfaction in a sample of persons with spinal cord injury. *Top Spinal Cord Inj Rehabil*. 1998;4(1):56-72.
3. Tasiemski T, Kennedy P, Gardner BP, Taylor N. The association of sports and physical recreation with life satisfaction in a community sample of people with spinal cord injuries. *NeuroRehabilitation*. 2005;20(4):253-265.
4. Dalyan M, Cardenas D, Gerard B. Upper extremity pain after spinal cord injury. *Spinal Cord*. 1999;37(3):191-195.
5. Lal S. Premature degenerative shoulder changes in spinal cord injury patients. *Spinal Cord*. 1998;36(3):186-189.
6. Akbar M, Balean G, Brunner M, et al. Prevalence of rotator cuff tear in paraplegic patients compared with controls. *J Bone Joint Surg*. 2010;92(1):23-30.
7. Jain NB, Higgins LD, Katz JN, Garshick E. Association of shoulder pain with the use of mobility devices in persons with chronic spinal cord injury. *PM&R*. 2010;2(10):896-900.
8. Zebracki K, Chlan K, Vogel L. Long-term outcomes of pediatric-onset spinal cord injury. In: Vogel LC, Zebracki K, Betz RR, Mulcahey, eds. *Spinal Cord Injury in the Child and Young Adult*. London: Wiley; 2015:359-375.
9. Ballinger DA, Rintala DH, Hart KA. The relation of shoulder pain and range-of-motion problems to functional limitations, disability, and perceived health of men with spinal cord injury: A multifaceted longitudinal study. *Arch Phys Med Rehabil*. 2000;81(12):1575-1581.
10. Boninger ML, Towers JD, Cooper RA, Dicianno BE, Munin MC. Shoulder imaging abnormalities in individuals with paraplegia. *J Rehabil Res Dev*. 2001;38(4):401.
11. Subbarao JV, Klopstein J, Turpin R. Prevalence and impact of wrist and shoulder pain in patients with spinal cord injury. *J Spinal Cord Med*. 1995;18(1):9-13.
12. Hwang M, Zebracki K, Chlan K, Vogel L. Longitudinal changes in medical complications in adults with pediatric-onset spinal cord injury. *J Spinal Cord Med*. 2014;37(2):171-178.
13. National SCI Statistical Center. *Spinal Cord Injury (SCI) Facts and Figures at a Glance*. Birmingham, AL: Author; 2016. <https://www.nscisc.uab.edu/Public/Facts%202016.pdf>
14. Paralyzed Veterans of America Consortium for Spinal Cord Medicine. Preservation of upper limb function following spinal cord injury: A clinical practice guideline for health-care professionals. *J Spinal Cord Med*. 2005;28(5):434.
15. Boninger ML, Souza AL, Cooper RA, Fitzgerald SG, Koontz AM, Fay BT. Propulsion patterns and pushrim biomechanics in manual wheelchair propulsion. *Arch Phys Med Rehabil*. 2002;83(5):718-723.
16. SmartWheel. Out-Front. http://www.out-front.com/smartwheel_dataoutput.php. Accessed August 27, 2018.
17. Slavens BA, Schnorenberg AJ, Aurit CM, et al. Biomechanics of pediatric manual wheelchair mobility. *Front Bioeng Biotechnol*. 2015;3.
18. De Groot S, Veeger H, Hollander A, Van Der Woude L. Consequence of feedback-based learning of an effective hand rim wheelchair force production on mechanical efficiency. *Clin Biomech*. 2002;17(3):219-226.
19. De Groot KK, Hollingsworth HH, Morgan KA, Morris CL, Gray DB. The influence of verbal training and visual feedback on manual wheelchair propulsion. *Disabil Rehabil Assist Technol*. 2009;4(2):86-94.
20. Kotajarvi BR, Basford JR, An K-N, Morrow DA, Kaufman KR. The effect of visual biofeedback on the propulsion effectiveness of experienced wheelchair users. *Arch Phys Med Rehabil*. 2006;87(4):510-515.
21. Richter WM, Kwarciak AM, Guo L, Turner JT. Effects of single-variable biofeedback on wheelchair handrim biomechanics. *Arch Phys Med Rehabil*. 2011;92(4):572-577.
22. Pett MA. *Nonparametric Statistics for Health Care Research: Statistics for Small Samples and Unusual Distributions*. Newbury Park, CA: Sage Publications; 2015.
23. Boninger ML, Koontz AM, Sisto SA, Dyson-Hudson TA. Pushrim biomechanics and injury prevention in spinal cord injury: Recommendations based on CULP-SCI investigations. *J Rehabil Res Dev*. 2005;42(3):9.
24. Sullivan KJ, Kantak SS, Burtner PA. Motor learning in children: Feedback effects on skill acquisition. *Phys Ther*. 2008;88(6):720-732.