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Pushrim biomechanics and injury prevention in spinal cord injury: Recommendations based on CULP-SCI investigations

Michael L. Boninger, MD;[1–2]* Alicia M. Koontz, PhD, RET;[1–2] Sue Ann Sisto, PhD;[3–4] Trevor A. Dyson-Hudson, MD;[3–4] Michael Chang, MD, PhD;[5] Robert Price, MSME;[5] Rory A. Cooper, PhD[1–2]

[1]Human Engineering Research Laboratories, Departments of Physical Medicine and Rehabilitation, University of Pittsburgh, Bioengineering and Rehabilitation Science and Technology, Pittsburgh, PA; [2]Department of Veterans Affairs, Center of Excellence in Wheelchairs and Related Rehabilitation Engineering, Pittsburgh, PA; [3]Department of Physical Medicine and Rehabilitation, University of Medicine and Dentistry of New Jersey—New Jersey Medical School, Newark, NJ; [4]Kessler Medical Rehabilitation Research and Education Corporation, West Orange, NJ; [5]Department of Rehabilitation Medicine, University of Washington, Seattle, WA

Abstract—Over 50 percent of manual wheelchair users with spinal cord injury (SCI) are likely to develop upper-limb pain and injury. The majority of studies related to pain have implicated wheelchair propulsion as a cause. This paper draws from a large multisite trial and a long-standing research program to make specific recommendations related to wheelchair propulsion that may decrease the risk of upper-limb injury. The studies include over 60 subjects over 1 yr after a traumatic SCI below the second thoracic level. Specific aspects of the propulsive stroke that may relate to injury include cadence, magnitude of force, and the pattern of the hand during the nonpropulsive part of the stroke. Lower peak forces, slower cadence, and a circular propulsive stroke in which the hand falls below the pushrim during recovery may help prevent injury. In addition, wheelchair users should use the lightest weight adjustable wheelchair possible. Future work should include interventional trials and larger studies that allow for more complex statistical models that can further detail the relationship between wheelchair propulsion, user characteristics, and upper-limb injuries.

Key words: arm, biomechanics, carpal tunnel syndrome, equipment, prevention, rehabilitation, repetitive strain injury, rotator cuff injury, spinal cord injury, technique, wheelchair.

INTRODUCTION

For many individuals with spinal cord injury (SCI), independence depends on the integrity of their upper limbs [1]. Unfortunately, activities like wheelchair propulsion and

Abbreviations: CTS = carpal tunnel syndrome, CULP-SCI = Collaboration on Upper Limb Pain in Spinal Cord Injury, MRI = magnetic resonance imaging, NCS = nerve conduction study, NIOSH = National Institute of Occupational Safety and Health, NRC = National Research Council, SCI = spinal cord injury, 3-D = three dimensional, VA = Department of Veterans Affairs.

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*Address all correspondence to Michael L. Boninger, MD; Professor and Research Director; Department of Physical Medicine and Rehabilitation, University of Pittsburgh, 3471 5th Avenue, Suite 201, Pittsburgh, PA 15213; 412-365-4850; fax: 412-365-4858. Email: boninger@pitt.edu

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transfers place great demands on the bones, joints, and soft tissues of the upper limbs. These essential activities can hasten the aging process, leading to injury and pain [2]. Cross-sectional studies have reported the prevalence of shoulder pain in individuals with SCI to be between 31 and 73 percent [3–6] and the prevalence of carpal tunnel syndrome (CTS) to be between 49 and 73 percent [7–10]. In all these studies, the authors suggest that the repetitive trauma associated with wheelchair propulsion and transfers is, in part, responsible for these injuries.

The impact of pain is considerable. In one of the largest studies on upper-limb pain, Sie et al. found that significant pain was present in 59 percent of individuals with tetraplegia and 41 percent of individuals with paraplegia [11]. Significant pain was defined as pain requiring analgesic medication, pain associated with two or more activities of daily living, or pain severe enough to result in cessation of activity. The tasks most commonly associated with upper-limb pain in individuals with SCI (e.g., work/school, transfers, outdoor wheeling, and driving) are the activities necessary for independence and community integration [1,3,12–13]. As these previously mastered activities become more difficult, the secondary disabilities they cause may further affect the individual's adjustment, self-perception, and involvement in satisfying and rewarding activities [2]. Lundqvist et al. found that pain was the only factor correlated with lower quality-of-life scores [14].

Preventing upper-limb pain in wheelchair users may be possible. A body of literature exists in the area of ergonomics that is often used to prevent injuries in workers. Task performance modification based on ergonomic analysis has been proven to reduce the incidence of pain and cumulative trauma disorders of the upper limb in various work settings [15–20]. This paper reviews the aspects of pushrim biomechanics relevant to injury prevention. By design, we focus on work and methods completed at the University of Pittsburgh and the Department of Veterans Affairs (VA) Pittsburgh Healthcare System and with our partners in a collaborative study, Collaboration on Upper Limb Pain in SCI (CULP-SCI). The CULP-SCI is a multisite study funded jointly by the VA and the Department of Education. Collaborative partners with the University of Pittsburgh include the University of Washington and the Kessler Medical Rehabilitation Research and Education Corporation (West Orange, NJ). The lead investigators are authors on this paper. During the discussion, and as part of the methods, we introduce in other literature; however, our intent is not to comprehensively review, but rather to derive practice recommendations based on our work.

METHODS

All the studies discussed in the **Table** have common components of data collection. What is presented here is a brief summary. For greater detail on the methodology and data analysis, refer to the individual studies.

Subject Recruitment

In each study, subjects were recruited from two primary sources: wheelchair vendors and discharge records following initial inpatient rehabilitation from inpatient SCI units in the region. In each instance, a letter was sent to the individuals requesting that they participate in the research study. Subjects were recruited in this manner so all individuals with SCI could be identified, not just those currently being followed through regular clinic visits. To be included in the studies, subjects had to have a traumatic SCI at the second thoracic level or below occurring >1 yr before to the start of the study. Subjects were not excluded if they had pain, unless they reported that pain interfered with their ability to propel a wheelchair. These individuals needed to use a manual wheelchair with 24 in. wheels full-time for mobility and be able to provide informed consent. All subjects in all studies provided written informed consent prior to participation in the study and in accordance with the University of Pittsburgh and Department of Veteran's Affairs Institutional Review Board requirements. The **Table** summarizes the subject characteristics for the CULP-SCI papers referenced.

Kinematic System

Two Optotrak three-camera motion-analysis systems by Northern Digital, Inc. (Waterloo, Canada), were used for this component of data collection (**Figure 1** shows the complete laboratory setup). These systems can collect real-time three-dimensional (3-D) data. The use of two cameras enabled visualization of both sides of the subjects. Markers were attached to the skin as shown in **Figure 2**. Markers were also attached to the chest wall and the temporal-mandibular joint. All kinematic data were collected at 60 Hz.

Table.
Summary of studies and subject characteristics.

Published Study	Subject Characteristics		
	Age	Years After SCI	Gender (M/F)
Boninger ML, Cooper RA, Baldwin MA, Shimada SD, Koontz A. Wheelchair pushrim kinetics: body weight and median nerve function. Arch Phys Med Rehabil. 1999;80(8):910–15.	34.9 ± 8.2 (Mean ± SD)	12.0 ± 12.0 (Mean ± SD)	23/11
Boninger ML, Impink BG, Cooper RA, Koontz AM. Relation between median and ulnar nerve function and wrist kinematics during wheelchair propulsion. Arch Phys Med Rehabil. 2004; 85(7):1141–45.	Mean = 38.9 Range 18–65	Mean = 12.2 Range 1–30	27/8
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):718–23.	35.1 ± 9.3 (Mean ± SD)	11.0 ± 6.1 (Mean ± SD)	27/11
Shimada SD, Robertson RN, Bonninger ML, Cooper RA. Kinematic characterization of wheelchair propulsion. J Rehabil Res Dev. 1998;35(2):210–18.	31.0 ± 7.94 (Mean ± SD)	Not Known	5/2
Boninger ML, Baldwin MA, Cooper RA, Koontz AM, Chan L. Manual wheelchair pushrim biomechanics and axle position. Arch Phys Med Rehabil. 2000;81(5):608–13.	35.2 ± 9.3 (Mean ± SD)	11.3 ± 6.1 (Mean ± SD)	28/12
Boninger ML, Dicianno BE, Cooper RA, Towers JD, Koontz AM, Souza AL. Shoulder MRI abnormalities, wheelchair propulsion, and gender. Arch Phys Med Rehabil. 2003; 84(11):1615–20.	32.8 ± 9.0 (Mean ± SD)	10.4 ± 5.9 (Mean ± SD)	8/6
Boninger ML, Towers JD, Cooper RA, Dicianno BE, Munin MC. Shoulder imaging abnormalities in individuals with paraplegia. J Rehabil Res Dev. 2001;38(4):401–8.	35.0 ± 9.9 (Mean ± SD)	11.5 ± 5.3 (Mean ± SD)	19/9

SCI = spinal cord injury SD = standard deviation M = male F = female

Kinetic System

The SMART^{Wheel} (Three Rivers Holdings, LLC, Mesa, AZ) was used for the collection of kinetic data. The SMART^{Wheel} can measure 3-D forces and moments occurring at the pushrim [21]. SMART^{Wheels} were placed on both sides of each subject's wheelchair. Use of the SMART^{Wheels} did not change the camber, axle position, or diameter of the subjects' normal pushrim.

Wheelchair Dynamometer

After the subject's wheelchair was fitted with SMART^{Wheels}, the wheelchair was secured to a wheelchair dynamometer. Subjects propelled their wheelchairs on the dynamometer to acclimate themselves to the experimental setup. The resistance of the dynamometer is comparable to rolling over a tile surface [22]. Subjects pushed their wheelchairs at different speeds (0.9 m/s, 1.8 m/s, and a self-selected speed). Propulsion speed was displayed on a 17 in. computer screen placed in front of the subjects. Subjects were asked to propel until they reached a steady state as determined by the investigators; upon reaching steady state, subject data were collected for 20 s. The subjects rested approximately 1 min between trials, while the kinetic and kinematic data were checked for errors. The kinetic data were filtered at 30 Hz. The filter was an eighth-order, zero-phase, digital Butterworth type [23].

Kinematic Analysis

To determine stroke patterns, we plotted the *x*- and *y*-coordinate positions of the third metacarpophalangeal joint for each subject, and a single investigator reviewed the patterns and classified them into semicircular, single loop-over-propulsion, double loop-over-propulsion, and arcing (**Figure 3**). For studies of wrist motion, a local

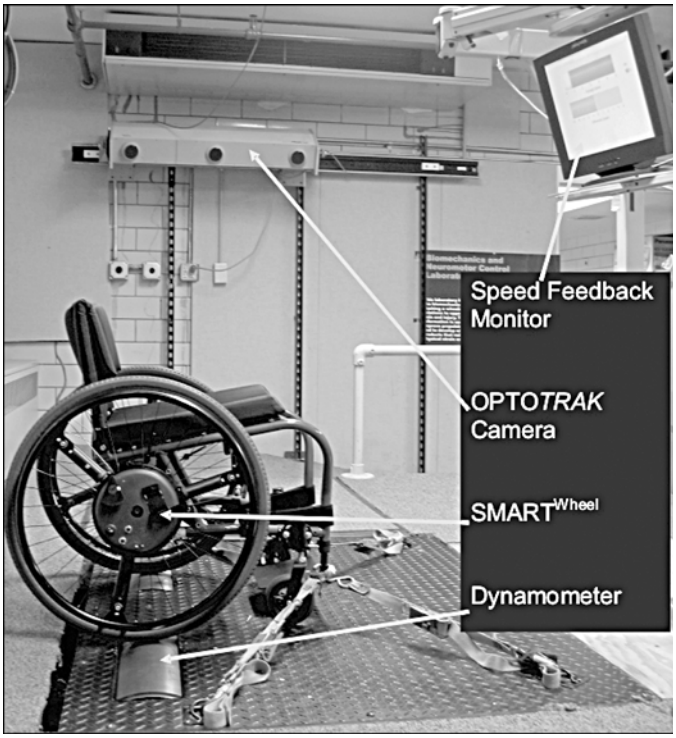

Figure 1.
Biomechanics laboratory in Department of Veterans Affairs Pittsburgh Healthcare System.

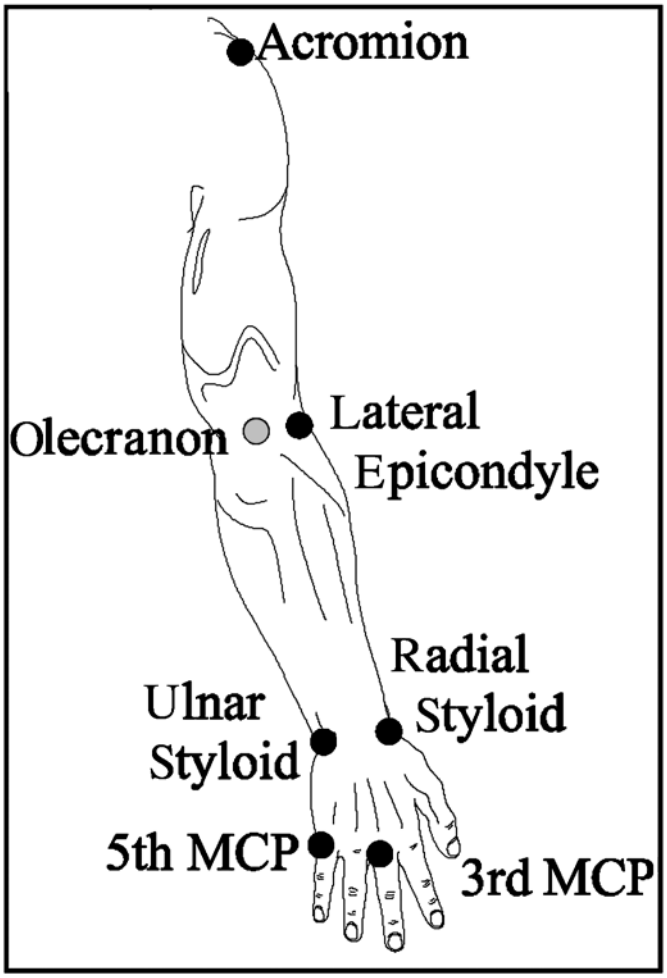

Figure 2.
Kinematic marker locations. Markers were also attached to chest wall and temporal-mandibular joint. MCP = metacarpophalangeal. (Reprinted from *Archives of Physical Medicine and Rehabilitation*, 83(5):718–23, Boninger ML et al.: "Propulsion Patterns and Pushrim Biomechanics in Manual Wheelchair Propulsion," ©2002 American Congress of Rehabilitation Medicine and American Academy of Physical Medicine and Rehabilitation.)

coordinate system for the wrist was developed [24]. The first axis was defined as a line pointing from the midpoint between the radial and ulnar styloids to the third metacarpophalangeal joint. The second axis was defined as perpendicular to the first axis and pointed out of the back of the hand/wrist. Rotations about this axis represented ulnar and radial deviation. The third axis was defined as perpendicular to the plane formed by the first two axes, and pointed from the midpoint of the wrist through the radial styloid. Movements about this axis represented flexion and extension. Wrist angles were averaged over the first five strokes.

Kinetic Analysis

For each stroke, the SMART^{Wheel} provided forces and moments in three global reference planes. The resultant force, which is the total force applied to the pushrim, was calculated by vector addition of F_x, F_y, and F_z [21,25]. We rotated the global force components, F_x and F_y, to obtain a radial force component directed toward the axle of the wheel and a tangential force component directed tangential to the pushrim [25]. We computed the rate of rise of the resultant force by taking the derivative of the resultant force with respect to time and then determining the maximum value during the first third of the stroke to capture initial impact loading on the pushrim. All calculations were completed with MATLAB (The MathWorks, Inc., Natick, Massachusetts). Key kinetic variables of resultant force, frequency, and rate of rise of resultant force were calculated from the first five strokes collected at steady state. The mean of the variables was then obtained to give a single value for each variable at

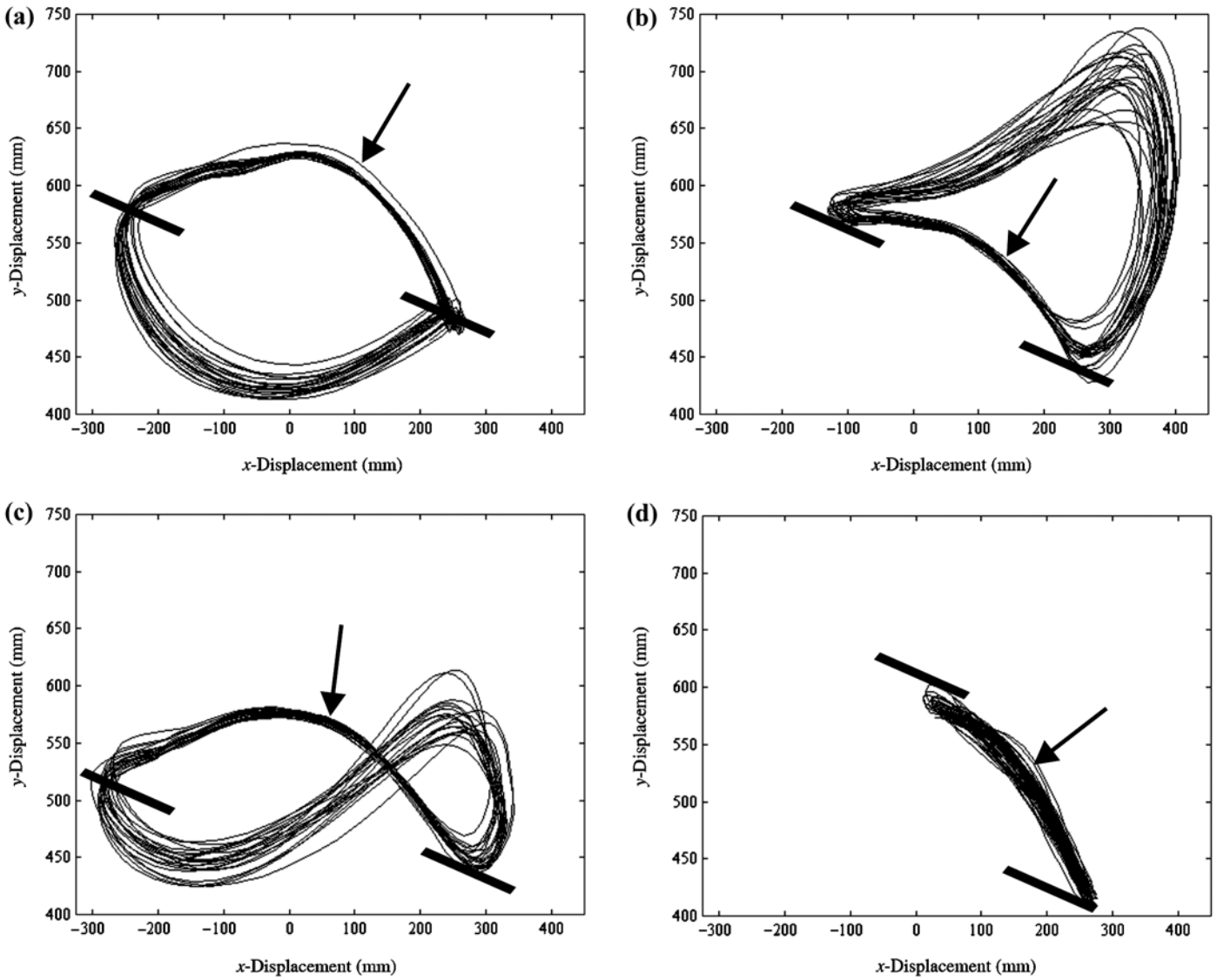

Figure 3.
Plots of *x*- and *y*-coordinates of third metacarpophalangeal marker of over 10 wheelchair propulsion cycles. Each plot represents frequently seen individual pattern: **(a)** semicircular, **(b)** single loop-over propulsion, **(c)** double loop-over propulsion, and **(d)** arcing. Heavy lines in figure indicate contact and end points. Arrow points to period where hand is on pushrim. (Reprinted from A*rchives of Physical Medicine and Rehabilitation*, 80(8):910–15, Boninger ML et al.: "Wheelchair Pushrim Kinetics: Body Weight and Median Nerve Function," ©1999 American Congress of Rehabilitation Medicine and American Academy of Physical Medicine and Rehabilitation.)

each speed. Using the output of the SMART^{Wheel}, we determined the cadence of the propulsive stroke and defined it as strokes/s. Details of the statistical analysis are presented separately for each paper [26–31].

Nerve Conduction Studies

Each subject had bilateral upper-limb nerve conduction studies (NCSs) as described by Boninger et al. [26]. All NCSs were completed by one of three American Board of Electrodiagnostic Medicine-certified technicians blinded to other subject information. Motor and sensory studies of the both the median and ulnar nerve were completed. Median nerve damage, which would be indicated by lower amplitude and longer latency responses, is the underlying pathology for CTS. Subjects were dropped subjects from the analysis if all median and

ulnar motor and sensory latencies or amplitudes were abnormal. This was done to exclude individuals with peripheral polyneuropathy.

RECOMMENDATIONS

Force

Peak forces should be minimized during wheelchair propulsion. The first study of 34 subjects with paraplegia found a significant relationship between weight and function of the median nerve. However, weight is related to rolling resistance, and therefore force needed to propel a wheelchair (**Figure 4**). In addition, both height and weight are related to median nerve function [32–33]. Height, weight, and weight-normalized pushrim forces were successfully incorporated into linear regression models predicting median nerve sensory amplitude and latency. For both models, higher weight-normalized forces corresponded with worse median nerve function [26]. The specific force variable that was most significantly related to median nerve function was rate of rise of resultant force. Individuals who more rapidly loaded the pushrim during the propulsive stroke had worse median nerve function.

In work not yet published, we again found force to be related to risk of median nerve injury. In this study, 23 manual wheelchair users with paraplegia were tested twice, an average of 3.4 yr apart. NCSs were completed at each test session and a biomechanical analysis of propulsion was completed at the first session. Using a regression model, we once again found force to be a factor in progression of median nerve injury over time. When we forced median motor latency at time one into the statistical model, peak weight normalized resultant force positively correlated with median motor latency at the end of testing, or time two ($p < 0.01$). Thus, people who pushed with greater force relative to body weight had worsening of NCSs over time. Although not definitive, the findings support the theory that wheelchair propulsion technique can lead to adverse changes in the median nerve.

Cadence

Cadence or push frequency should also be minimized during wheelchair propulsion. This recommendation is based on the 1999 study by Boninger et al. [26]. In addition to peak forces and rate of rise of force being correlated with impaired median nerve function, Boninger et al. also saw a relationship with frequency. Increasing frequency was significantly related to lower median amplitude ($p < 0.01$).

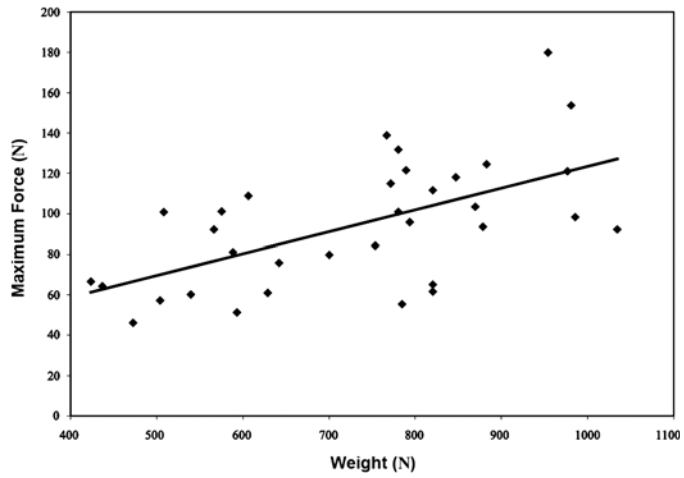

Figure 4.
Plot of peak resultant pushrim force in Newtons versus weight in Newtons. Data were collected at 2.2 m/s steady-state propulsion speed. Line represents best fit ($r = 0.59$, $p < 0.001$).

The relationship with frequency was further clarified in a recent paper related to wrist motion [27]. In this study, the relationship between wrist motion and median and ulnar nerve function was investigated in 35 individuals with paraplegia. Increased wrist flexion and extension range of motion was related to higher median and ulnar nerve amplitudes, or less nerve injury. To explain these findings, we looked at the relationship between range of motion and cadence, as well as force. Greater range of motion was associated with lower cadence and force.

Recovery Patterns

When propelling a wheelchair, the user should let the hand drift below the pushrim during the recovery phase (**Figure 3**). The recovery pattern is the path the hand follows when not on the pushrim. In two separate studies, Boninger et al. [28] and Shimada et al. [29], we have investigated the relationship between the recovery pattern and biomechanics. **Figure 3** presents the recovery patterns discussed in the Boninger et al. 2002 publication involving 38 subjects [28]. In this study, we found that the single-loop-over propulsion was the most common pattern. However, the semicircular pattern was associated with a lower cadence and the greatest time spent in propulsion relative to recovery. In other words, wheelchair users who followed a semicircular pattern hit the pushrim

less frequently and used more of the pushrim to go the same speed.

Wheelchair Factors

Wheelchair users should be provided with the lightest adjustable wheelchairs possible. Body weight has been found to relate to injuries at both the wrist and shoulder. In addition, the known relationship between weight and rolling resistance means that heavier wheelchairs require the user to push with more force. Adjustability is another key factor in assuring good wheelchair biomechanics. In an analysis of 40 individuals with SCI, we found that individuals who had their axles further forward with respect to the shoulder had a slower cadence and a decrease in rate of rise of the resultant force [30]. As stated previously, both findings have been associated with median nerve injury. The height of the axle with respect to the shoulder is also important. Decreasing the vertical distance between the shoulder and axle enables more of the pushrim to be available for the propulsive stroke. This results in greater push angles and allows force to be imparted to the wheelchair pushrim for a longer time, thus decreasing the frequency of propulsion necessary to maintain speed. **Figure 5** summarizes these findings. However, too low a position can cause excessive abduction at the shoulder.

Subject Factors

Subjects should be advised to avoid weight gain and be aware that women may be at greater risk of shoulder injury. Our studies have found that subject weight and gender may impact risk of injury [31,34]. We tracked 14 wheelchair users with SCI for an average of 2.5 yr and found that females were much more likely to have progression of shoulder magnetic resonance imaging (MRI) abnormalities than males ($p = 0.001$) [31]. In this study, half the subjects showed progression of MRI abnormalities. Six of the seven with progression were women, and no women in the group improved or stayed the same [31].

Subject weight was correlated to injury in a number of our studies. In an analysis of 28 individuals, all of whom had MRIs and X rays of the shoulder, we found body weight to be positively correlated to the number of imaging abnormalities seen in both X ray ($p < 0.01$) and MRI ($p < 0.01$) [34]. In addition, we found body weight to be related to median nerve injury in the studies outlined under the cadence and force paragraphs above [26]. As noted previously, individuals who weigh more use more force to push their wheelchairs, which increases their risk of developing upper-limb injuries.

DISCUSSION

This paper outlines scientific evidence from the CULP-SCI group for practical recommendations related to wheelchair setup and propulsion. Based on the information provided here, we recommend that wheelchair users be instructed to take long, smooth propulsive strokes that use as much of the pushrim as possible. When releasing the rim, the user should let the hand drift below the pushrim during the recovery stage. Long, smooth strokes should minimize both the cadence and the peak forces applied. By design, the results and recommendations given here were based on work completed at the University of Pittsburgh and the Pittsburgh VA and were not intended to be a systematic literature review. However, in a number of areas, other literature relates to our recommendations, briefly discussed next.

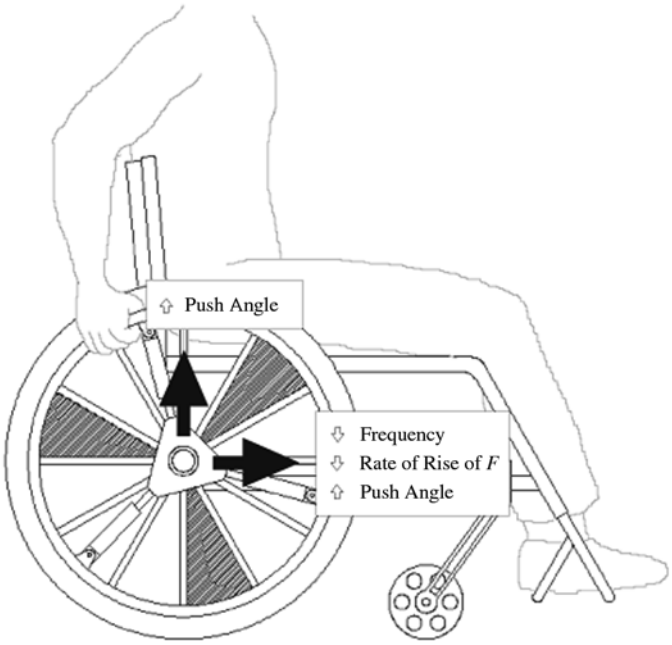

Figure 5.
Summary of effect of changing axle position on pushrim biomechanics (force [*F*]). Large arrows represent direction of axle movement to cause effect noted. (Reprinted from *Archives of Physical Medicine and Rehabilitation*, 81(5):608–13, Boninger ML et al.: "Manual Wheelchair Pushrim Biomechanic and Axel Position," ©2002 American Congress of Rehabilitation Medicine and American Academy of Physical Medicine and Rehabilitation.)

Three large evidence-based reviews have been conducted of the link between repetitive tasks and upper-limb injury. In 1997, the National Institute of Occupational Safety and Health (NIOSH) reviewed the epidemiologic evidence of this link [35]. In 1999, the National Research Council (NRC) published "Work-related musculoskeletal disorders: a review of the evidence" [36]. In 2001, the NRC, together with the Institute of Medicine, completed a review, "Musculoskeletal disorders and the workplace" [37]. These comprehensive reviews have found strong links between work activities, physiologic and psychophysical conditions at work, and injury.

One conclusion from these comprehensive reviews is that limiting the frequency of repetitive tasks should reduce the risk of injury. A number of studies have strongly implicated frequency of task completion as a risk factor for repetitive strain injury and/or pain at the wrists [38–41] and shoulder [42–44]. Although the majority of studies are correlative and do not prove cause-and-effect relationships, longitudinal work has found similar results [45]. Wheelchair propulsion, with strokes occurring approximately once per second, exceeds what the majority of studies consider a frequent task. For instance, a study by Silverstein et al. found greater prevalence of CTS in workers with highly repetitive jobs [39]. In the Silverstein study, a cycle time of <30 s was considered high frequency. Wheelchair propulsion cycle time is usually <1 s [25]. If a wheelchair user pushes his or her chair 16 min/day, he or she will exceed the number of repetitions a factory worker in a high-cycle task would complete in an 8 h day.

Another conclusion that can be drawn from the reviews and the ergonomics literature is that peak forces should be minimized during wheelchair propulsion. Higher forces during tasks are correlated with injuries and/or pain at the wrist [38–39,41] and shoulder [43–44]. Longitudinal studies have also found that higher loads or high-force work predicts risk of development of pain or injury [45–47]. The forces defined as "high" in these studies are almost always exceeded during wheelchair propulsion [25]. For example, one study defined high force as 39 N [39]. Wheelchair users propel with forces routinely over 70 N [26]. Another study noted that pulling or pushing a mass over 50 kg was related to shoulder pain [48]. Clearly, the average individual with SCI weighs much more than 50 kg (110 lb). Maintaining an ideal body weight is one way to minimize forces during wheelchair propulsion and transfers.

The recommendation to increase the length of propulsion stroke and decrease frequency could lead to increased range of motion at the wrist, and some ergonomics literature indicates that increased range of motion could lead to injury. However, the 1997 NIOSH review indicated that insufficient evidence exists of a link between wrist range of motion, or posture, and injury [35]. The finding that increased range of motion at the wrist was associated with lower forces and frequency further explains our findings of less nerve injury in those who use greater range of motion [27]. The range of motion found in our study [27] and a Rao et al. study [49] does not include extreme wrist angles, where the wrist is likely more prone to injury.

Less information is available in support of the exact recovery pattern to use. Recent work found that when subjects without disability were trained in both the semicircular and the arc style of propulsion, the arc or pumping style was more mechanically efficient (arc = 7.1 percent vs. semicircular = 6.7 percent) [50]. This same study also found increased cadence with the arc style (range 61–70) compared to the semicircular style (range 53–56). Because the arc style results in a greater than 18 percent increase in cadence, we recommend the semicircular style, despite the 6 percent decrease in mechanical efficiency. However, we emphasize that taking long, smooth propulsive strokes is likely the most important advice to give.

Many authors have made strong arguments for providing wheelchair users with the lightest weight adjustable wheelchairs possible. One study directly compared ultralight and depot wheelchairs and found that when using an ultralight wheelchair, individuals with SCI pushed at faster speeds, traveled longer distances, and used less energy [51]. This was believed to be due in part to lower rolling resistance secondary to decreased weight. Another factor that can contribute to lower rolling resistance is a higher quality chair, which likely has better wheelchair components such as tires and bearings, as well as better long-term maintenance. A more forward axle position has been found to decrease rolling resistance and improve efficiency [52–53]. A lower seat position has been associated with greater upper-limb motions [53–54], greater hand contact angles [30,54], lower frequency, and higher mechanical efficiency [54]. Because axle position affects stability [55], the wheelchair should be set up with the axle as far forward as possible, provided the patient feels stable. The best seat height is the point at which the elbow is flexed between

100° and 120° when the hand is resting on the top dead center of the pushrim [30,54]. An alternative method that can be used to approximate the same position and angle is to have the individual rest with arms hanging at the side so that the fingertips are at the center of rear wheel hub.

Note that the results and recommendations stated in this article are based on the analysis of approximately 60 manual wheelchair users with paraplegia from the Pittsburgh area. Although this is a large number of subjects compared to most articles on wheelchair users and most biomechanics studies, much more could be learned from a larger study. In addition, these studies were limited to wheelchair users with paraplegia, who may not represent wheelchair users with other disabilities. While we believe that these findings are applicable to manual wheelchair users with other disabilities, caution should be exercised when applying the results to other groups. Furthermore, most of the results are based on biomechanics at the pushrim and injury at the wrist. Modeling that allows for determination of forces and moments at specific joints will likely provide additional insight.

Based on the work presented in this paper, the U.S. Department of Education, through the National Institute for Disability and Rehabilitation Research and through the Department of Veterans Affairs, awarded funding to the CULP-SCI for a multicenter study of wheelchair biomechanics. This longitudinal study will involve over 150 subjects and will combine epidemiologic and biomechanical methods. We are hopeful that this study will further define the relationship between upper-limb injury and both wheelchair propulsion biomechanics and subject and wheelchair characteristics. We also hope that this multisite study will lead to further recommendations that may help prevent upper-limb pain and injury in manual wheelchair users.

CONCLUSION

Substantial scientific evidence is available that supports specific recommendations related to the type of manual wheelchair an individual should receive, how it should be set up, and how it should be propelled. Continued work is needed to strengthen this evidence. In addition, work should begin on interventional trials to see if applying these recommendations results in positive changes for patients who rely on manual wheelchairs.

REFERENCES

1. Pentland WE, Twomey LT. Upper limb function in persons with long term paraplegia and implications for independence: Part II. Paraplegia. 1994;32(4):219–24.
2. Gerhart KA, Bergstrom E, Charlifue SW, Menter RR, Whiteneck GG. Long-term spinal cord injury: functional changes over time. Arch Phys Med Rehabil. 1993;74(10): 1030–34.
3. Pentland WE, Twomey LT. The weight-bearing upper extremity in women with long term paraplegia. Paraplegia. 1991;29:521–30.
4. Gellman H, Sie I, Waters RL. Late complications of the weight-bearing upper extremity in the paraplegic patient. Clin Orthop Relat Res. 1988;233(August):132–35.
5. Bayley JC, Cochran TP, Sledge CB. The weight-bearing shoulder. The impingement syndrome in paraplegics. J Bone Joint Surg [Am]. 1987;69:676–78.
6. Wylie EJ, Chakera TM. Degenerative joint abnormalities in patients with paraplegia of duration greater than 20 years. Paraplegia. 1988;26:101–6.
7. Aljure J, Eltorai I, Bradley WE, Lin JE, Johnson B. Carpal tunnel syndrome in paraplegic patients. Paraplegia. 1985; 23:182–86.
8. Gellman H, Chandler DR, Petrasek J, Sie I, Adkins R, Waters RL. Carpal tunnel syndrome in paraplegic patients. J Bone Joint Surg [Am]. 1988;70:517–19.
9. Tun CG, Upton J. The paraplegic hand: Electrodiagnostic studies and clinical findings. J Hand Surg [Am]. 1988;13: 716–19.
10. Davidoff G, Werner R, Waring W. Compressive mononeuropathies of the upper extremity in chronic paraplegia. Paraplegia. 1991;29:17–24.
11. Sie IH, Waters RL, Adkins RH, Gellman H. Upper extremity pain in the postrehabilitation spinal cord injured patient. Arch Phys Med Rehabil. 1992;73:44–48.
12. Curtis KA, Roach KE, Applegate EB, Amar T, Benbow CS, Genecco TD, Gualano J. Development of the Wheelchair User's Shoulder Pain Index (WUSPI). Paraplegia. 1995;33(5):290–93.
13. Dalyan M, Cardenas DD, Gerard B. Upper extremity pain after spinal cord injury. Spinal Cord. 1999;37(3):191–95.
14. Lundqvist C, Siosteen A, Blomstrand C, Lind B, Sullivan M. Spinal cord injuries. Clinical, functional, and emotional status. Spine. 1991;16(1):78–83.
15. Carson R. Reducing cumulative trauma disorders: use of proper workplace design. AAOHN J. 1994;42(6):270–76.
16. Beck L. Your company needs an ergonomics program. Mod Mat Handling. 1987;Oct:62–68.
17. Drury C, Kleiner B, Zahorjan J. How can manufacturing human factors help save a company: Intervention at high

and low levels. Human Factors Society 33rd Annual Meeting; 1989. p. 687–89.

18. Hoyt W. Carpal tunnel syndrome: Analysis and prevention. Prof Saf. 1984;29(11):16–21.
19. Chatterjee DS. Workplace upper limb disorders: a prospective study with intervention. Occup Med. 1992;42(3):129–36.
20. McKenzie F, Storment J, Van Hook P, Armstrong TJ. A program for control of repetitive trauma disorders associated with hand tool operations in a telecommunications manufacturing facility. Am Ind Hyg Assoc J. 1985;46(11): 674–78.
21. Cooper RA, Robertson RN, VanSickle DP, Boninger ML, Shimada SD. Methods for determining three-dimensional wheelchair pushrim forces and moments—A technical note. J Rehabil Res Dev. 1997;34(2):162–70.
22. DiGiovine CP, Cooper RA, Boninger ML. Dynamic calibration of a wheelchair dynamometer. J Rehabil Res Dev. 2001;38(1):41–55.
23. Cooper RA, DiGiovine CP, Boninger ML, Shimada SD, Robertson RN. Frequency analysis of 3-dimensional pushrim forces and moments for manual wheelchair propulsion. Automedica. 1998;16:355–65.
24. Shimada SD, Cooper RA, Boninger ML, Koontz AM, Corfman TA. Comparison of three different models to represent the wrist during wheelchair propulsion. IEEE Trans Neural Syst Rehabil Eng. 2001;9(3):274–82.
25. Boninger ML, Cooper RA, Robertson RN, Shimada SD. 3-D pushrim forces during two speeds of wheelchair propulsion. Am J Phys Med Rehabil. 1997;76(5):420–26.
26. Boninger ML, Cooper RA, Baldwin MA, Shimada SD, Koontz A. Wheelchair pushrim kinetics: body weight and median nerve function. Arch Phys Med Rehabil. 1999; 80(8):910–15.
27. Boninger ML, Impink BG, Cooper RA, Koontz AM. Relation between median and ulnar nerve function and wrist kinematics during wheelchair propulsion. Arch Phys Med Rehabil. 2004;85(7):1141–45.
28. 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):718–23.
29. Shimada SD, Robertson RN, Bonninger ML, Cooper RA. Kinematic characterization of wheelchair propulsion. J Rehabil Res Dev. 1998;35(2):210–18.
30. Boninger ML, Baldwin MA, Cooper RA, Koontz AM, Chan L. Manual wheelchair pushrim biomechanics and axle position. Arch Phys Med Rehabil. 2000;81(5):608–13.
31. Boninger ML, Dicianno BE, Cooper RA, Towers JD, Koontz AM, Souza AL. Shoulder MRI abnormalities, wheelchair propulsion, and gender. Arch Phys Med Rehabil. 2003;84(11):1615–20.
32. Letz R, Gerr F. Covariates of human peripheral nerve function: I. Nerve conduction velocity and amplitude. Neurotoxicol Teratol. 1994;16(1):95–104.
33. Nathan PA, Keniston RC, Myers LD, Meadows KD. Obesity as a risk factor for slowing of sensory conduction of the median nerve in industry. A cross-sectional and longitudinal study involving 429 workers. J Occup Med. 1992; 34(4):379–83.
34. Boninger ML, Towers JD, Cooper RA, Dicianno BE, Munin MC. Shoulder imaging abnormalities in individuals with paraplegia. J Rehabil Res Dev. 2001;38(4):401–8.
35. Musculoskeletal disorders and workplace factors: A critical review of epidemiology for work related musculoskeletal disorders of the neck, upper extremity, and low back. Cincinnati, OH: National Institute for Occupational Safety and Health, Publications Dissemination; 1997.
36. Work-related musculoskeletal disorders: a review of the evidence. Washington, DC: National Academy Press; 1999.
37. Musculoskeletal disorders and the workplace: Low back and upper extremities. Washington (DC): National Academy Press; 2001.
38. Werner RA, Franzblau A, Albers JW, Armstrong TJ. Median mononeuropathy among active workers. Are there differences between symptomatic and asymptomatic workers. Am J Ind Med. 1998;33(4):374–78.
39. Silverstein B, Fine L, Stetson D. Hand-wrist disorders among investment casting plant workers. J Hand Surg [Am]. 1987;12(5 Pt 2):838–44.
40. Loslever P, Ranaivosoa A. Biomechanical and epidemiological investigation of carpal tunnel syndrome at workplaces with high risk factors. Ergonomics. 1993;36:537–55.
41. Roquelaure Y, Mechali S, Dano C, Fanello S, Benetti F, Bureau D, Martin YH, Derriennic F, Penneau-Fontbonne D. Occupational and personal risk factors for carpal tunnel syndrome in industrial workers. Scand J Work Environ Health. 1997;23(5):364–69.
42. Cohen RB, Williams GR. Impingement syndrome and rotator cuff disease as repetitive motion disorders. Clin Orthop. 1998;(351):95–101.
43. Frost P, Bonde JP, Mikkelsen S, Andersen JH, Fallentin N, Kaergaard A, Thomsen JF. Risk of shoulder tendinitis in relation to shoulder loads in monotonous repetitive work. Am J Ind Med. 2002;41(1):11–18.
44. Andersen JH, Kaergaard A, Frost P, Thomsen JF, Bonde JP, Fallentin N, Borg V, Mikkelsen S. Physical, psychosocial, and individual risk factors for neck/shoulder pain with pressure tenderness in the muscles among workers performing monotonous, repetitive work. Spine. 2002;27(6): 660–67.
45. Fredriksson K, Alfredsson L, Thorbjornsson CB, Punnett L, Toomingas A, Torgen M, Kilbom A. Risk factors for neck

and shoulder disorders: a nested case-control study covering a 24-year period. Am J Ind Med. 2000;38(5):516–28.

46. Stenlund B, Goldie I, Hagberg M, Hogstedt C, Marions O. Radiographic osteoarthrosis in the acromioclavicular joint resulting from manual work or exposure to vibration. Br J Ind Med. 1992;49:588–93.
47. Stenlund B, Goldie I, Hagberg M, Hogstedt C. Shoulder tendinitis and its relation to heavy manual work and exposure to vibration. Scand J Work Environ Health. 1993;19: 43–49.
48. Hoozemans MJ, van der Beek AJ, Frings-Dresen MH, van der Woude LH, van Dijk FJ. Pushing and pulling in association with low back and shoulder complaints. Occup Environ Med. 2002;59(10):696–702.
49. Rao SS, Bontrager EL, Gronley JK, Newsam CJ, Perry J. Three-dimensional kinematics of wheelchair propulsion. IEEE Trans Rehabil Eng. 1996;4(3):152–60.
50. de Groot S, Veeger HE, Hollander AP. van der Woude LH. Effect of wheelchair stroke pattern on mechanical efficiency. Am J Phys Med Rehabil. 83(8):640–49.
51. Beekman CE, Miller-Porter L, Schoneberger M. Energy cost of propulsion in standard and ultralight wheelchairs in people with spinal cord injuries. Phys Ther. 1999;79(2): 146–58.
52. Brubaker CE. Wheelchair prescription: An analysis of factors that affect mobility and performance. J Rehabil Res Dev. 1986;23:19–26.
53. Hughes CJ, Weimar WH, Sheth PN, Brubaker CE. Biomechanics of wheelchair propulsion as a function of seat position and user-to-chair interface. Arch Phys Med Rehabil. 1992;73:263–69.
54. van der Woude LHV, Veeger DJ, Rozendal RH, Sargeant TJ. Seat height in handrim wheelchair propulsion. J Rehabil Res Dev. 1989;26:31–50.
55. Majaess GG, Kirby RL, Ackroyd-Stolarz SA, Charlebois PB. Influence of seat position on the static and dynamic forward and rear stability of occupied wheelchairs. Arch Phys Med Rehabil. 1993;74(9):977–82.

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