

## ORIGINAL ARTICLE

# Stroke Pattern and Handrim Biomechanics for Level and Uphill Wheelchair Propulsion at Self-Selected Speeds

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**ABSTRACT.** Richter WM, Rodriguez R, Woods KR, Axelson PW. Stroke pattern and handrim biomechanics for level and uphill wheelchair propulsion at self-selected speeds. *Arch Phys Med Rehabil* 2007;88:81-7.

**Objectives:** To investigate the natural stroke patterns of wheelchair users pushing on a level surface, to determine if users adapt their stroke patterns for pushing uphill, and to assess whether there are biomechanic advantages to one or more of the stroke patterns.

**Design:** Case series.

**Setting:** Biomechanics laboratory.

**Participants:** Twenty-six manual wheelchair users with a spinal cord injury.

**Intervention:** Subjects pushed their own wheelchairs at self-selected speeds on a research treadmill set to level, 3°, and 6° grades. Stroke patterns were measured using a motion capture system. Handrim biomechanics were measured using an instrumented wheel.

**Main Outcome Measures:** Stroke patterns were classified for both level and uphill propulsion according to 1 of 4 common classifications: arcing, semi-circular, single-looping (SLOP), and double-looping (DLOP). Biomechanic outcomes of speed, peak handrim force, cadence, and push angle were all compared across stroke classifications using an analysis of variance.

**Results:** Only 3 of the 4 stroke patterns were observed. None of the subjects used the semi-circular pattern. For level propulsion, the stroke patterns were fairly balanced between arcing (42%), SLOP (31%), and DLOP (27%). Subjects tended to change their stroke pattern for pushing uphill, with 73% of the subjects choosing the arcing pattern by the 6° grade. No statistically significant differences were found in handrim biomechanics or subject characteristics across stroke pattern groups.

**Conclusions:** Wheelchair users likely adapt their stroke pattern to accommodate their propulsion environment. Based on the large percentage of subjects who adopted the arcing pattern for pushing uphill, there may be benefits to the arcing pattern for pushing uphill. In light of this and other recent

work, it is recommended that clinicians not instruct users to utilize a single stroke pattern in their everyday propulsion environments.

**Key Words:** Biomechanics; Rehabilitation; Wheelchairs.

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OVER HALF OF THE MANUAL wheelchair user population is estimated to have developed upper-extremity pain and injury.<sup>1-8</sup> The consequences of upper-extremity injuries are significant, including decreased quality of life due to pain, decreased mobility, shoulder and wrist surgeries, and the eventual need for a powered wheelchair. Propulsion technique is one aspect of wheelchair use that is believed to be associated with upper-extremity injury.<sup>9-14</sup> Therefore, improving propulsion technique may help to reduce or prevent the development of overuse injuries. This study examined 1 aspect of propulsion technique, the stroke pattern or trajectory of the hand during propulsion.

When pushing, the user's hands are forced to follow the path of the handrim. However, between pushes users can choose how they want to move their hands while preparing for the next push. A variety of different hand trajectory patterns have been classified during the recovery phase of the propulsion cycle, including semi-circular, single looping (SLOP), double looping (DLOP), and arcing, illustrated in figure 1.<sup>15-20</sup> Although it is not understood why users implement different strategies during recovery, there have been several studies investigating the potential advantages of the various patterns.

Sanderson and Sommer<sup>15</sup> investigated the stroke pattern of 3 competitive wheelchair racers while pushing on a level treadmill. Two of the subjects used the semi-circular pattern and 1 subject used the arcing pattern.<sup>15</sup> The "pumping" motion of the arcing pattern was hypothesized to require more work due to the abrupt changes in the velocity of the arms and therefore likely to be less efficient than the semi-circular pattern. Veeger et al<sup>16</sup> analyzed stroke patterns in 2 wheelchair athletes pushing on a treadmill. The 2 subjects were a subset of the 5 subjects who participated in the study and were chosen because one used the arcing and the other the semi-circular pattern. There were no clear differences in push angle, upper-extremity joint ranges, or mechanical efficiency found between the stroke patterns.<sup>16</sup> Chou et al<sup>17</sup> observed the stroke patterns used by 3 experienced wheelchair users and 3 nonwheelchair users while pushing on level ground. The experienced users were found to use the semi-circular pattern while the nonusers implemented the arcing pattern.<sup>17</sup> The investigators argued that the semi-circular pattern is likely to be more efficient than the arcing pattern because it was chosen by the experienced users.

Vanlandewijck et al<sup>18</sup> studied 40 wheelchair basketball players pushing at 2 speeds on a level treadmill. The investigators did not classify stroke patterns for the population but did note there were remarkable differences between subjects.<sup>18</sup> It was

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Letter to the editor from Dr. Boninger and our response can be found on the last 2 pages, after the references.

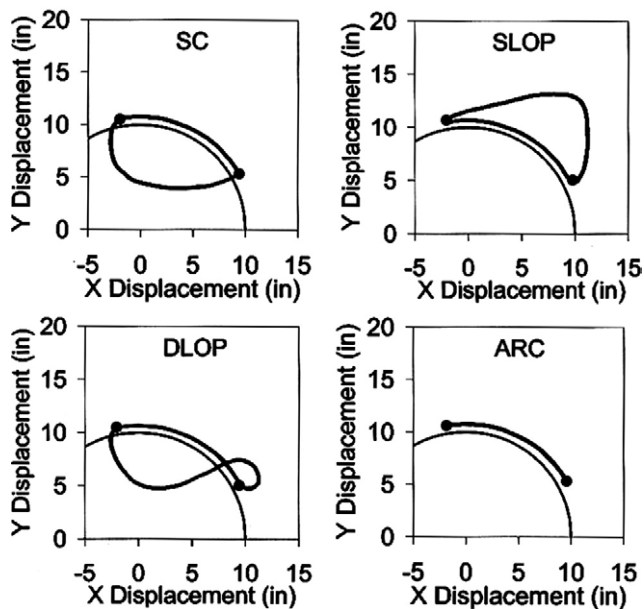


Fig 1. Stroke pattern classifications during wheelchair propulsion (stylized illustrations). The hand is constrained to follow the handrim during the push but the user is free to choose how to follow through between pushes. In the arcing pattern, the user's hand travels back along the handrim between pushes. Abbreviations: ARC, arcing; DLOP, double looping; SC, semi-circular; SLOP, single-looping.

found that the subjects did not change their stroke pattern with increasing speed but that the average path length of the hand for the group increased by 20% for the faster propulsion condition. The investigators also found that the wheelchair continued to accelerate after the user released the handrim, due to the inertial forces acting on the wheelchair-user system as the arms swing backward and/or the trunk returns to an upright position. As a result, the researchers cautioned against performing research on stationary ergometers, because these inertial forces of propulsion are ignored. Despite this recommendation, all the stroke pattern studies that have followed have been done on stationary ergometers.

Shimada et al<sup>19</sup> investigated stroke patterns for 7 wheelchair users pushing on a stationary ergometer set to simulate level propulsion. In the moderate speed condition, 2 subjects used the semi-circular pattern, 4 used the DLOP pattern, and 1 used the SLOP pattern.<sup>19</sup> Those subjects who used the semi-circular pattern were shown to exhibit statistically longer push times, shorter recovery times, greater elbow extension range of motion (ROM), and greater shoulder abduction ROM. Boninger et al<sup>20</sup> studied stroke patterns in a relatively large population of 38 manual wheelchair users while pushing on a stationary ergometer set to simulate level propulsion. It was found that 45% of the subjects used the SLOP pattern, 25% used the DLOP pattern, 16% used the semi-circular pattern, and 14% used the arcing pattern.<sup>20</sup> The semi-circular pattern was found to be associated with a lower cadence (push frequency) and a greater ratio of push to coast time. Because, in an earlier study,<sup>10</sup> this same research group had found an association between push cadence and incidence of wrist injury, they recommended training wheelchair users to use the semi-circular pattern.

However, a study by de Groot et al<sup>21</sup> calls this recommendation into question. In this study, 24 inexperienced wheelchair

users were asked to propel on a stationary ergometer using each of 3 stroke patterns, arcing, semi-circular, and SLOP.<sup>21</sup> As with the Boninger study,<sup>20</sup> the semi-circular pattern was found to result in a lower push frequency and a greater push time than the arcing pattern. However, the arcing pattern was found to require less metabolic demand than the semi-circular pattern, suggesting that reducing push frequency and maximizing metabolic efficiency may be competing interests.

Both of the Boninger and de Groot studies were done on stationary ergometers, which simulate pushing on a level surface but ignore some of the inertial effects of actual propulsion. It is unclear whether the results of these studies translate to everyday wheelchair propulsion; where not only does the wheelchair accelerate but is also used to negotiate challenging terrain like pushing uphill. The purpose of this study was (1) to investigate the natural stroke patterns of wheelchair users pushing on a level surface, (2) to determine if wheelchair users adapt their stroke patterns for pushing uphill, and (3) to assess whether there are biomechanic advantages to 1 or more of the stroke patterns.

## METHODS

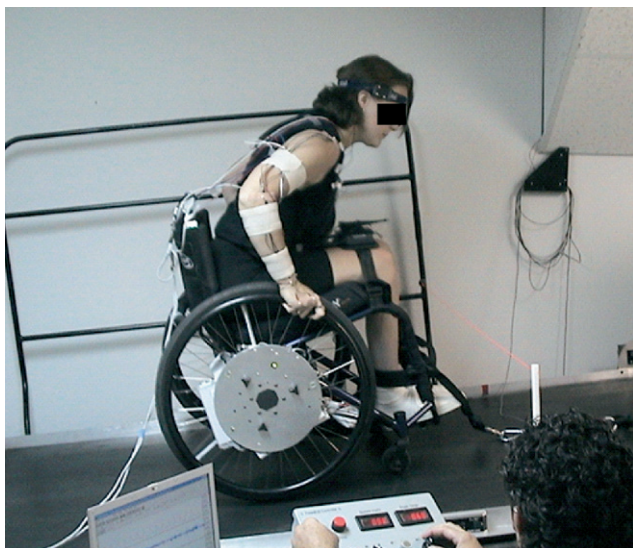
### Participants

The protocol received institutional review board (IRB) approval prior to recruiting subjects. We recruited 25 manual wheelchair users to participate. The study goal was to get at least 20 subjects because that is the minimum required for consideration in the Paralyzed Veterans of America clinical practice guidelines on the preservation of upper-limb function following spinal cord injury.<sup>22</sup> To be included in the study, subjects must: (1) have been full-time users of a manual wheelchair, (2) have been comfortable propelling a wheelchair for periods of 2 minutes, (3) have had a wheelchair with 61-cm (24-in) diameter rear wheels, (4) have had full use of their upper extremity, and (5) have had no medical conditions that could be aggravated by wheelchair propulsion. The IRB-approved consent form was signed by all subjects prior to participation.

### Experimental Protocol

We weighed the subjects in their wheelchairs using digital postal scales under each wheel. Subjects then transferred out of their wheelchairs and the weight of the wheelchairs was determined. Body weight was calculated as the difference between the 2 weight measures. Subject injury level was recorded and classified as being either low-level (T12-L5), mid-level (T7-11), or high-level (T2-6). The subjects' rear wheels were replaced with propulsimeter instrumented test wheels that had standard uncoated handrims.<sup>a</sup> All subjects who participated in the study also used uncoated handrims. Subjects were then transferred back into their wheelchairs and were fitted with a motion capture marker on the third metacarpophalangeal joint (MPJ) of their right hands.

We conducted propulsion trials on a multigrade research treadmill with a safety system. A spotter at the front of the treadmill controlled the safety tether. Subjects practiced pushing on the treadmill at a range of speeds and then chose a comfortable speed for level, 3°, and 6° grades. After resting for at least 5 minutes, subjects pushed for 35 pushes on level, 30 pushes on the 3° grade, and 25 pushes on the 6° grade, all at their self-selected speeds. Motion of the right hand and wheel were tracked using the motion capture system. Loading on the right handrim was measured using



**Fig 2.** The experimental setup used in this study included a research treadmill, an instrumented wheel, and a motion-capture system.

the right propulsometer. The experimental setup is illustrated in figure 2.

### Instrumentation

The propulsometer is a custom instrumented wheel that is capable of measuring the dynamic 3-dimensional forces and moments applied to the handrim during propulsion. The propulsometer measures handrim loads using a commercially available 6-degree-of-freedom load cell.<sup>b</sup> The load cell is mounted at the hub of the wheel, and the handrim is coupled to the wheel through the load cell. Loads applied to the handrim pass through the load cell and are then transferred to the wheel. The plane of the handrim is aligned with the measurement plane of the load cell, thereby ensuring equivalency between loads applied to the handrim and those measured at the load cell. Measurements from the load cell are transferred to a data collection computer using a high-speed wireless LAN connection. Handrim kinetics were measured at 200Hz and filtered using a fourth-order Butterworth digital filter with a 20-Hz cutoff frequency.<sup>23</sup> The dynamic offset was then removed from each channel and the calibration matrix applied, resulting in conditioned force and torque outputs.<sup>24</sup>

We measured hand and wheel kinematics using an active-marker motion capture system.<sup>c</sup> A single marker was used to track the trajectory of the third MPJ of the hand. Additional markers were located on the propulsometer and were used to resolve wheel angle and determine the center of the propulsometer hub. Motion capture markers were activated using a wireless transceiver. An external trigger was used to ensure the kinematic data collection was synchronized with the kinetic data collection. The sampling rate of the motion capture system was set to 100Hz. The data were filtered using a fourth-order Butterworth digital filter with a 10-Hz cutoff frequency.<sup>25</sup> The effective sampling rate of the kinematic data were then increased to match the kinetic data (200Hz) by applying a cubic spline to each channel measured.

### Data Reduction

We used the last 20 pushes from each grade condition in the analysis.<sup>26</sup> The resultant force on the handrim was defined as the vector sum of the 3 local force components. The resultant force on the handrim was normalized by body weight to facilitate comparison across subjects. Pushes were identified by periods of active loading on the handrim. For each push analyzed, the peak force, push angle, and cycle time were all determined. Individual push characteristics were then averaged over each 20-push set. Power output was determined using the average axial moment (moment about the wheel axle), net wheel displacement and trial time. Push frequency was calculated as the inverse of the average cycle time. A hub-hand vector was defined from the propulsometer hub to the third MPJ marker. Stroke patterns were graphed for each 20-push set using the coordinates of the hub-hand vector in the median plane and identified as 1 of the 4 classifications illustrated in figure 1: arcing, SLOP, DLOP, or semi-circular. Data reduction was automated using custom programs developed in Matlab.<sup>d</sup>

### Statistical Analyses

We calculated descriptive statistics for each of the continuous biomeasures both for the entire population and for sub-populations of subjects within each stroke pattern group. Categorical data (sex, injury level) were tabulated to determine frequencies of occurrence in each stroke pattern group.

We compared stroke patterns using an analysis of variance for the continuous dependent variables: propulsion speed, peak handrim force, push angle, push frequency, and body weight. Bonferroni post hoc tests were used to assess the statistical strength of differences between stroke patterns. Chi-square tests were similarly used to assess the strength of differences between stroke patterns for categorical data. Statistical analyses were repeated for each of the 3 grade conditions. Differences were determined to be statistically significant for *P* less than .05. All statistical tests were completed using SPSS statistical software.<sup>e</sup>

## RESULTS

### Participants

Twenty-six manual wheelchair users (19 men, 7 women) participated in the study. Subjects were on average  $36 \pm 11$  years old, with an average of  $17 \pm 11$  years of wheelchair experience. Subject characteristics are listed in table 1. Each subject had a spinal cord injury.

### Handrim Biomechanics

The resulting handrim biomechanics for the entire subject population is given in the last row of table 2. The subjects slowed down as grade was increased, with an average 63%

**Table 1: Subject Characteristics**

Characteristics	Values
Subjects (N)	26
Mean age $\pm$ SD (y)	$36 \pm 11$
Mean wheelchair use $\pm$ SD (y)	$17 \pm 11$
Sex (M/F)	19/7
Injury level (low/mid/high)	9/13/4
Mean weight $\pm$ SD (kg)	$69.8 \pm 15.7$

Abbreviations: F, female; M, male; SD, standard deviation.

**Table 2: Handrim Biomechanics for Each Stroke Pattern Group and the Entire Subject Population**

Stroke Pattern	n	Level			
		Speed (m/s)	Peak Force (body weight)	Push Angle (deg)	Push Freq (Hz)
DLOP	7	1.04±0.24	0.074±0.013	105.2±22.2	1.18±0.18
SLOP	8	1.14±0.21	0.073±0.027	118.9±26.5	0.99±0.26
Arcing	11	1.24±0.23	0.083±0.020	102.5±14.5	1.16±0.29
All	26	1.16±0.23	0.078±0.021	108.3±21.3	1.11±0.26
3° Slope					
DLOP	3	0.69±0.13	0.117±0.030	90.2±10.1	1.06±0.18
SLOP	5	0.72±0.14	0.123±0.039	95.9±14.4	1.04±0.18
Arcing	18	0.79±0.19	0.140±0.020	98.5±21.4	1.10±0.20
All	26	0.77±0.17	0.134±0.026	97.1±18.9	1.08±0.19
6° Slope					
DLOP	1	0.36±NA	0.158±NA	69.4±NA	0.88±NA
SLOP	6	0.43±0.16	0.158±0.051	88.2±29.4	0.79±0.08
Arcing	19	0.43±0.17	0.176±0.035	77.1±16.2	0.91±0.21
All	26	0.43±0.16	0.170±0.038	80.7±19.5	0.87±0.19

NOTE. Values are mean ± SD, except for DLOP on the 6° grade because only a single subject used that stroke pattern. None of the differences between the stroke pattern groups were found to be statistically significant. Abbreviation: NA, not available.

decrease in speed from the level to 6° grade condition ( $P=.000$ ). Peak forces on the handrim increased markedly with increasing grade, with an average 218% increase from the level to the 6° grade condition ( $P=.000$ ). Push angle and cadence (push frequency) both decreased with increasing grade, with 25.5% and 21.6% decreases from the level to the 6° grade conditions, respectively ( $P=.002$ ,  $P=.042$ ).

While the subjects chose slower speeds when on a grade, power output was found to increase substantially from level propulsion to uphill propulsion. Power output for level, 3°, and 6° grades ± SD was 10.2±4.8, 39.2±10.6, and 41.9±16.9W, respectively. The power output for the 3° and 6° grades were found to be 2.84 and 3.11 times the power output of the level condition ( $P=.000$ ,  $P=.000$ ). Differences between the 3° and 6° grades were not significant ( $P=.150$ ).

### Stroke Patterns

Stroke patterns were found to be highly consistent within each subject for any particular grade condition. The frequency of stroke patterns for each of the grade conditions is given in figure 3. Only 3 of the 4 possible stroke pattern classifications were observed in this study. None of the subjects used the semi-circular pattern. The number of subjects who used each of the remaining 3 classifications was fairly balanced for level propulsion, with the largest number of subjects using the arcing pattern (42%). However, once subjects began pushing uphill, many of the subjects who were not using the arcing pattern began to use it. Nineteen (73%) of the 26 subjects were using the arcing pattern by the time they got to the 6° grade. An example of a transitioning recovery pattern is shown in figure 4 for a subject who transitioned from the SLOP pattern to the arcing pattern. By the 6° grade, only 1 subject was still using the DLOP pattern.

### Subject Characteristics Across Stroke Patterns

Subject weight did not differ significantly between stroke pattern groups. Again, because there was only a single subject

in the DLOP group on the 6° grade, it was not included in the statistical analysis. Chi-square analyses of sex and injury level did not detect any significant differences between the stroke pattern groups, nor were there any clear trends.

### Handrim Biomechanics Across Stroke Patterns

The resulting handrim biomechanics for each stroke pattern group are given in table 2. Because there was only 1 subject using the DLOP pattern on the 6° grade, that condition was not included in the statistical analysis. None of the differences were found to be even close to reaching statistical significance. The lowest adjusted  $P$  value was .224, for propulsion speed between the arcing and DLOP groups on level. Most adjusted  $P$  values were equal to 1.0. In addition, there were no clear trends in the results that would suggest a pattern.

### DISCUSSION

This study represents the first investigation of stroke patterns among wheelchair users that has included both level and uphill propulsion conditions. Pushing uphill is more strenuous than on level ground. Peak handrim forces in this study were found to be over twice as high when pushing up a 6° hill as when rolling on a level surface. A 6° slope is not an extreme condition. A standard accessible ramp into a building is 4.8° (1:12) in the United States.<sup>27</sup> Everyday propulsion environments can involve climbing much steeper hills. Pushing up a 2.9° ramp has been reported to require as much as 66% of the wheelchair user's shoulder flexion strength.<sup>28</sup> It is important that research methodologies take a variety of environmental conditions into account in order to maximize the applicability of the results to typical everyday usage.

None of the 26 subjects used the semi-circular stroke pattern that has been identified as having biomechanic benefits.<sup>19-21</sup> For simulated level propulsion, Boninger et al<sup>20</sup> found that the smallest number of subjects (14%) used the arcing pattern. In contrast, the largest number of subjects used the arcing pattern (42%) for level propulsion in this study. It is possible that the differences in results between these studies occurred by random chance. However, it is more likely that differences in experimental setups influenced the results. The above-mentioned studies were all done using a stationary ergometer, where the wheelchair does not actually move during propulsion. Pushing on a treadmill is actual rather than simulated propulsion, where the wheelchair accelerates in response to

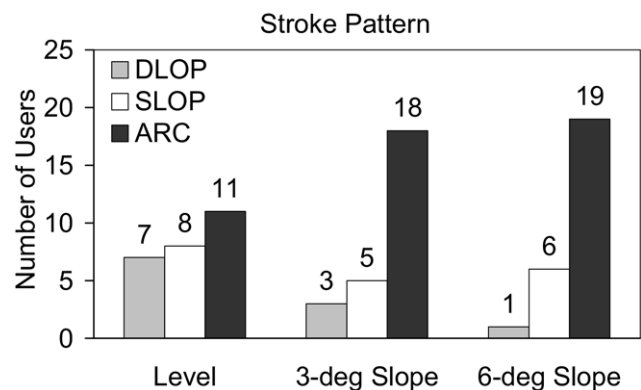


Fig 3. The freely chosen stroke patterns were fairly balanced for level propulsion, but the arcing pattern became the most popular for pushing uphill.

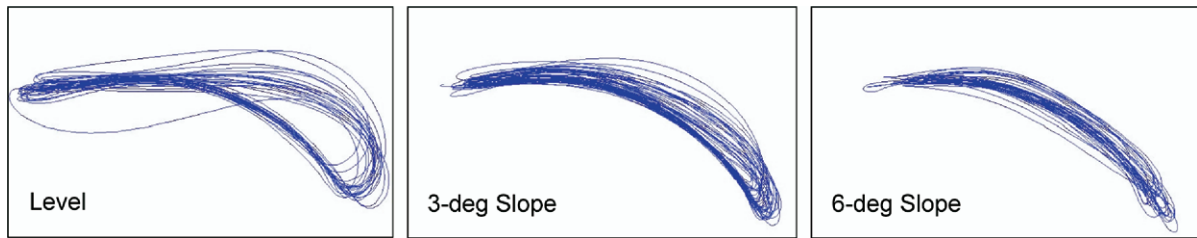


Fig 4. The transition in stroke pattern from SLOP to arcing for 1 subject as the grade was increased.

each push and the individual inertial properties of propulsion are preserved. A postpush acceleration of the wheelchair, which occurs when coasting, results from the pulling back of the arms.<sup>18</sup> The semi-circular pattern is characterized by a smooth hand return after the push, without any abrupt changes in the velocity of the arms. As a result, the semi-circular pattern may not result in a postpush acceleration that is generated when using other stroke patterns.

While stroke patterns were varied for level propulsion, it became clear that for pushing uphill, arcing is the most popular pattern. Based on its popularity alone, it could be hypothesized to be the most biomechanically efficient. This hypothesis would be supported by the finding that the arcing pattern required less metabolic energy than did the semi-circular pattern for simulated level propulsion.<sup>21</sup> However, there may be reasons other than efficiency that draws users to the arcing pattern for pushing uphill. When pushing uphill, the user must maintain her balance and not tip backward. In addition, missing a push could mean losing control and rolling backward down the hill. With the arcing pattern, the user's hands remain close to the handrim when coasting, allowing her to make quick corrections. The SLOP pattern was the second most popular choice for pushing uphill. With the SLOP pattern, the user's hands are above the handrim, which allow her to push down and grip the handrim relatively quickly. Conversely, the DLOP pattern, much like the semi-circular pattern, may put the user at a disadvantage because her hands are well below the handrims and the arms need to be lifted up against gravity to make unexpected corrections. The role of stroke pattern on wheelchair control and balance has largely been ignored, perhaps due to the exclusive use of stationary ergometers in some research laboratories. Additional research is needed to better understand what, if any, functional benefits there are to the arcing and SLOP stroke patterns.

Previous research<sup>20,21</sup> suggests that use of the arcing pattern results in greater push frequencies. In the present study, there were no significant differences in push frequency between the arcing pattern and either of the SLOP or DLOP patterns. As described earlier, not finding any differences may be due to having tested in a more realistic propulsion environment. However, the lack of differences could also be attributed to the use of self-selected propulsion speeds. By not constraining propulsion speed across test subjects, variability in the biomechanical measures could be attributed to variations in speed. Future studies will include a common velocity condition to minimize this source of variability. Push frequency may also be affected by other factors not measured in this study, such as seat height. A user that is seated lower may have greater access to the handrim and can push through a greater angle, resulting in a reduced push frequency.<sup>29</sup> That same user may choose a stroke pattern in which the hand drops below the handrim during recovery simply because it is more comfortable than lifting it

above the handrim. In this case, the recovery pattern is not responsible for the decreased push frequency, but rather an artifact of a low seat position. Additional research is needed to better understand these relationships.

It is clear that the consequences of various stroke patterns are not fully understood and there is a need to do the fundamental research required to assess which pattern or patterns are best for individual wheelchair users. Based on the results of the study by Boninger et al,<sup>20</sup> the clinical practice guidelines for the Preservation of Upper Limb Function Following Spinal Cord Injury<sup>22</sup> recommend that wheelchair users implement the semi-circular pattern during everyday propulsion. These guidelines are described as a first step in the ongoing process of developing useful tools for preserving upper-limb function in people with spinal cord injury. The guidelines did not consider the study by de Groot et al,<sup>21</sup> which suggests that the arcing pattern may result in greater metabolic efficiency than the semi-circular pattern. Clinical professionals are cautioned against training wheelchair users to push with any particular stroke pattern until more is known about their consequences. A user's naturally chosen stroke pattern may turn out to be the best solution for that particular person, in that specific propulsion environment.

#### Study Limitations

The primary limitations of this study include: (1) the use of a small population of wheelchair users and (2) the use of self-selected speeds. While a population of 26 wheelchair users may be more than adequate for many study designs, it was not adequate in this study. For level propulsion, the numbers of users in each stroke pattern group were fairly balanced, but once on a grade, the group distributions became clearly unbalanced. The small number of subjects in the SLOP and DLOP pattern groups when on a grade limited the statistical power for those comparisons. The use of self-selected speeds was to ensure that subjects pushed in the most comfortable and natural environment as possible. The problem with this approach is that how fast someone pushes is related to their propulsion technique.<sup>30</sup> Comparisons cannot easily be made between 2 users who are pushing at different speeds. However, this is not so easily overcome. Two users of very different body weight who push at the same speed are also not directly comparable, because the heavier user will be working at a higher power output than the lighter user. This can be remedied by having the heavier user push at a lower treadmill grade, but that also confounds the comparison.

To get around the limitations of sample size and self-selected speeds, a repeated-measures study design can be used, so each subject pushes with each of the stroke patterns for each grade condition. This approach was taken by de Groot.<sup>21</sup> However, in the de Groot study, subjects did not have mobility impairments, nor did they have previous experience pushing a wheelchair. The rationale for this approach was to ensure that none of the

subjects would have a preferred technique. The limitation of the approach was the applicability to actual wheelchair users. Future studies will combine the repeated measures approach of the de Groot study and the multigrade treadmill approach used in this current study.

A secondary limitation of this study was the use of a treadmill. From a mechanical perspective, treadmill propulsion is nearly identical to over-ground propulsion. It only lacks the element of wind resistance. However, from a wheelchair operation perspective there are some fundamental differences. First, the user must maintain a fixed propulsion speed. This removes the option to slow down, whether due to desire or in response to a mistake such as missing a push. Second, the user must maintain a straight heading in order to avoid hitting the side rails of the treadmill. These aspects of pushing on a treadmill could lead subjects to be more conservative than they would be if pushing over ground. Future research will explore stroke patterns during over-ground propulsion.

### CONCLUSIONS

Wheelchair users are free to choose a stroke pattern during everyday propulsion. The results of this study suggest that wheelchair users will change their stroke pattern to accommodate their propulsion environment. Stroke patterns were fairly balanced between arcing, SLOP, and DLOP for level propulsion, with none of the subjects using the semi-circular pattern. On an uphill grade, most subjects used the arcing stroke pattern. There were no biomechanic advantages or disadvantages found for any one pattern. Our current level of understanding of stroke patterns is not adequate to serve as a basis for promotion of any 1 pattern over another. Additional focused research is needed to advance our understanding.

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  - b. ATI Industrial Automation, Pinnacle Pk, 1031 Goodworth Dr, Apex, NC 27539-3869.
  - c. Phoenix Technologies Inc, 4302 Norfolk St, Burnaby, BC V5G 4J9, Canada.
  - d. The MathWorks, 3 Apple Hill Dr, Natick, MA 01760-2098.
  - e. SPSS Inc, 233 S Wacker Dr, 11th Fl, Chicago, IL 60606.

## DEPARTMENTS

*Letters to the Editor***Preserving Upper-Limb Function in Spinal Cord Injury**

As chair of the Consortium for Spinal Cord Medicine (CSCM) development panel that put together the clinical practice guideline (CPG) on preserving upper-limb function in spinal cord injury,<sup>1</sup> I would like respond with a representative of one of the Consortium member organizations to the January 2007 article by Richter et al<sup>2</sup> wherein they recommend that a portion of the CPG not be followed. The specific CPG recommendation is that manual wheelchair users be educated to “allow the hand to drift down naturally, keeping it below the pushrim when not in actual contact with that part of the wheelchair.”<sup>1(p15-6)</sup> during the recovery phase of propulsion. Specifically, Richter states that “Our current level of understanding of stroke patterns is not adequate to serve as a basis for promotion of any 1 pattern over another.”<sup>2(p86)</sup>

The only data Richter presents for this conclusion are that his research team found no difference in propulsion biomechanics between people who allowed their hand to drop below the pushrim and those who did not. However, Richter clearly points out that his study would have had a hard time finding such differences because the research team did not control for speed: “Comparisons cannot easily be made between 2 users who are pushing at different speeds.”<sup>2(p85)</sup> The only other finding that led to recommending against following the guideline was that no users allowed their hands to drop below the pushrim while propelling on a tilted treadmill and it was not the most “popular” style chosen during level propulsion on a treadmill. Again, Richter qualifies this finding because, when propelling in the artificial environment of a treadmill, veering from a straight path or changing speed can cause you to hit a rail. Richter explains that treadmill testing may cause users to “be more conservative” or otherwise to be unnatural in propulsion of their wheelchair. A propulsion pattern that tracks along the pushrim is conservative. Another interpretation of the Richter findings might be that because more people used a style of propulsion in which their hands did not drop below the pushrim, there is a greater need to intervene. The CSCM CPG is focused on “preservation” of upper-limb function, not on current preference of stroke pattern.

Richter provides another justification for not following the guidelines—a study by de Groot et al.<sup>3</sup> In the de Groot study, unimpaired subjects were trained to propel a manual wheelchair using different recovery patterns. In that study, a pattern that tracks the pushrim was found to be 0.4% more mechanically efficient. However, this pattern caused an 18% increase in cadence. The de Groot study was not referenced in the CSCM guideline because it was published after a predetermined cutoff date for scientific literature relevant to the topic. However, this finding was discussed in a later article<sup>4</sup> not referenced by Richter. That article stated that the slightly greater mechanical efficiency is not worth the much higher cadence—a known risk factor for repetitive strain injury.<sup>5</sup>

In recommending that a portion of the guideline not be followed, Richter dismisses work completed using a roller system—a well-validated and widely used technique for studying wheelchair propulsion. The Richter study claims that treadmill propulsion is more realistic. While this may be true,

Richter provides no data to support this claim and, as noted above, there are drawbacks to the treadmill environment.

The CSCM guidelines were developed by an interdisciplinary group of expert clinicians and researchers. The English-language, scientific, published literature was searched thoroughly to find relevant articles. The evidence that led to the recommendations was graded by an independent expert methodologist who followed a strict, thoroughly described protocol for evaluating every article and grading the evidence supporting the recommendations. In addition, 3 independent ergonomics experts evaluated each recommendation for level of agreement with the ergonomics literature. Although the strength of their ratings varied, the methodologist and ergonomics experts concurred that the available evidence was consistent with this recommendation. Importantly, the panel also voted on each recommendation and the strength of the panel opinion was considered. In this vote, clinical experience was a factor used to judge the recommendation. The panel gave this recommendation its strongest level of support. Finally, the guideline was peer reviewed by over 40 content experts representing the more than 20 professional societies that make up the CSCM.

Given the limited data in the Richter study, the review process of the CPG, and the clinical input that went into the CPG, there is no reason to call into question the recommendation that users allow the hand to drift down below the pushrim when not in contact with the rim.

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### The author responds

The basis for the recommendation that users let their hands drift down below the handrims in a semi-circular path between pushes is a study by Boninger et al.<sup>1</sup> In that study, wheelchair users pushed on a stationary roller system and those subjects who naturally tended to use the semi-circular hand pattern exhibited a lower push cadence compared with the remaining subjects. There are limitations to the Boninger study that were not discussed in the published article. First, it was an observational study, so the effect of altering stroke pattern was not assessed. Second, the study results suggest that even those users who use the semi-circular pattern do not do so exclusively. Half of those users who pushed with the semi-circular pattern at 0.9m/s abandoned that style for another when pushing at 1.8m/s. Both the single-loop and arcing propulsion patterns saw increases in usage for the higher speed. We do not know why users adapted their push style for different speed conditions or what the consequences of forcing them to push with a fixed style would be.

Boninger's description of the de Groot et al<sup>2</sup> study needs clarification. First, an 18% increase in cadence was compared with a 0.4% decrease in mechanical efficiency. These 2 results are not directly comparable. The 18% increase is a relative change, while the 0.4% decrease is an absolute change (the unit of measure is percent). Second, there were 2 subject groups and the 18% increase in cadence was only for the slow group. The fast group showed an 8.9% increase in cadence. The weighted average of the 2 groups is 13.8%. By comparison, the relative decrease in mechanical efficiency was 6.7% (0.4% and 0.6% absolute changes). Based on this information, there is a clear tradeoff if one uses the semi-circular pattern. However, if push cadence is truly critical and outweighs the measured losses in efficiency, then the results of de Groot study would actually lead to choosing the single-loop pattern, not the semi-circular pattern. The single-loop pattern had both a lower average cadence than the semi-circular pattern and a higher mechanical efficiency than the semi-circular pattern.

Our study<sup>3</sup> provides additional evidence that we do not fully understand the role of various stroke patterns on the wheelchair user. The core finding of our study was simple: the number of wheelchair users using the arcing pattern increased from 42% on a level surface to 73% when pushing uphill. The histogram

(fig 3)<sup>3(p84)</sup> shows a sharp decrease in the use of the double-loop propulsion pattern and a dramatic rise in the number of users adopting the arcing pattern. None of the subjects used the semi-circular pattern. It seems misleading to suggest that users have a preference and choose a particular pattern. Our subjects were not educated in the various hand path classifications; they simply did what came naturally to them given the various propulsion conditions. It is up to us as researchers in this field to understand why various patterns are used. We suggested that the arcing pattern might be advantageous for pushing uphill because it keeps the user's hands close to the handrims, allowing him/her to quickly make corrections and to avoid rolling backward down the hill. This is particularly important when on a hill, because the user has very little time between letting go of the handrims and re-gripping them again. If this is true, it would imply that use of a particular pattern may be influenced by safety concerns and not exclusively by biomechanic factors alone.

Based on the evidence provided, I do not believe that we know enough about stroke patterns to recommend any 1 pattern for all wheelchair users in all propulsion conditions and environments.

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