INTRODUCTION

In a continuing effort to reduce the high prevalence of upper limb (UL) pain in manual wheelchair users [1], we have been working towards the development of training strategies to help improve the efficiency of wheelchair propulsion. This work has involved the development of an instrumented wheelchair wheel with real-time biofeedback, and several studies [2,3] of the equipment and techniques that will hopefully lead to better propulsion, less UL pain, and a higher quality of life.

METHODS

Biofeedback System: The path to better wheelchair propulsion began with the development of new instrumentation. The OptiPush Biofeedback System was designed to measure three-dimensional forces and moments applied to the handrim, and provide push-by-push feedback on 10 propulsion variables: braking torque, push cadence, contact angle, impact, peak force, push distance, smoothness and speed. The OptiPush Wheel is composed of a customized wheelchair wheel, anodized handrim, 3 aluminum beams, and an Instrumentation Module (Fig. 1), which houses the sensors and electrical components of the device, namely a 6 degree-of-freedom load cell, rotary encoder, and Bluetooth module. Data received by a designated computer are recorded at 200 Hz and filtered with a 4th order Butterworth digital low-pass filter with a 20-Hz cutoff frequency. Conditioned forces, torques and wheel angles are used to compute the biofeedback variables. Each variable can be displayed in a bar graph with a running average of the last 5 strokes. A target value can be set to help reach or maintain a desired value. For cadence, an auditory beep is also available for cadence. A validation study, which has been submitted for publication, was conducted to establish OptiPush measurement accuracy.

Biofeedback Training: As an initial step towards developing propulsion training guidelines, we studied the effects of single variable biofeedback. Thirty-one manual wheelchair users were enrolled in the study. Their rear wheels were replaced with an OptiPush wheel on the right side and a weighted wheel on the left side. Subjects were secured to a motor-driven treadmill, which was set to match his/her average overground speed and power output. An 1-minute normal propulsion trial was captured, then, one variable at a time, subjects were shown feedback of braking moment, cadence, contact angle, peak force, push distance, and smoothness. They were asked to make a maximum improvement for all variables and a targeted 10% improvement for cadence, contact angle, peak force, and push distance. Subjects were also asked to push with each of the other 3 identified stroke patterns [4].

The differences between each subject's normal propulsion trial and the biofeedback and stroke pattern trials were analyzed with Wilcoxin signed-rank tests and a pair of one way ANOVAs, respectively. Data from this study were also used to compare overground propulsion and treadmill propulsion. Paired t-tests were used to analyze the differences in the values of each propulsion variable for the overground and treadmill conditions.

RESULTS AND DISCUSSION

OptiPush Validation: The OptiPush was able to accurately measure wheel angle (0.02% error),
wheel speed (0.06% error), and handrim loads. The maximum errors in static force and torque were 3.80% and 2.05%, respectively. Dynamic measurements of planar forces ($F_x$ and $F_y$) and axle torque also had low error (-0.96 N to 0.83 N for force and 0.10 Nm to 0.14 Nm for torque) and were highly correlated ($r > .986$) with expected values.

Treadmill Propulsion: Compared to overground propulsion, the handrim kinetics ($N = 28$) resulting from treadmill propulsion were similar and highly correlated. Contact angle, peak force, average force, and peak axle moment differed by 1.6% or less across the two conditions. While not significant, power output and cadence tended to be slightly higher for the treadmill condition (3.5% and 3.6%, respectively), due to limitations in adjusting the treadmill grade. Based on these results, a motor-driven treadmill can serve as a valid substitute for overground wheelchair propulsion [2].

Effects of Single Variable Biofeedback: For 9 of the 11 conditions, subjects were able to significantly improve the value of the biofeedback variable [3]. For the 10% conditions, subjects exhibited good control over cadence, push distance, and contact angle, with deviations within 1% of the targets. On the other hand, subjects had difficulty making changes to peak force and smoothness.

Targeting one variable at a time had both positive and negative cross-variable effects. Most notable was the trade-off between peak force and cadence. Efforts to minimize cadence, and push distance, led to significant changes in all outcome variables, including a 153-173% increase in peak force. Maximizing contact angle also led to a significant 34% increase in peak force. The only biofeedback variable that led to a decrease in peak force was peak force, which had no significant indirect effects, but produced a 20% increase in cadence. To help wheelchair users make more significant reductions in peak force, we have redesigned the biofeedback display to show force throughout the stroke for each 3 degrees of contact angle (Fig. 2).

Effects of Stroke Pattern: Though still under analysis, the results of the stroke pattern testing suggest that the semi-circular (SC) and double-loop (DL) stroke patterns lead to beneficial handrim biomechanics. When using either pattern, subjects ($N = 25$) had the longest contact angles, lowest cadence values, and the smallest braking moments. Subjects also had the lowest UL muscle activity with the DL pattern. While the DL pattern had the highest peak force (60.7 N) of any pattern, this is attributed to a low cadence (0.75 Hz), further highlighting the trade-off between force and cadence.

Future work will include testing the effects of multi-variable biofeedback and optimum seat position on propulsion biomechanics, and establishing guidelines for balancing peak force and cadence values.

**REFERENCES**


**Table 1**: Direct and indirect effects of four key conditions from the single variable biofeedback study [3].

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadence</td>
<td>-64 (14)*</td>
<td>-30 (21)†</td>
<td>20 (33)</td>
<td>-67 (12)†</td>
</tr>
<tr>
<td>Contact Angle</td>
<td>25 (27)†</td>
<td>31 (22)*</td>
<td>-7 (15)</td>
<td>26 (21)†</td>
</tr>
<tr>
<td>Peak Force</td>
<td>154 (87)†</td>
<td>34 (42)*</td>
<td>-11 (17)*</td>
<td>173 (112)†</td>
</tr>
<tr>
<td>Push Distance</td>
<td>221 (119)†</td>
<td>65 (76)†</td>
<td>-11 (19)</td>
<td>255 (136)*</td>
</tr>
</tbody>
</table>

* Significant (p < .005) direct change, and † significant (p < .0008) indirect change from normal propulsion.