Feasibility of a bimanual, lever-driven wheelchair for people with severe arm impairment after stroke

Brendan W. Smith, Daniel K. Zondervan, Thomas J. Lord, Vicky Chan, and David J. Reinkensmeyer

Abstract— **Individuals with severe arm impairment after stroke are thought to be unable to use a manual wheelchair in the conventional bimanual fashion, because they cannot grip and push the pushrim with their impaired hand. Instead, they are often taught to propel a wheelchair with their good arm and leg, a compensatory strategy that encourages disuse and may cause asymmetric tone. Here, we show that four stroke survivors (9, 27 50 and 16 months post stroke) with severe arm impairment (upper extremity Fugl Meyer scores of 21, 17, 16 and 15 of 66 respectively) were able to propel themselves over-ground during ten, 3.3 meter movement trials, using a specially designed lever-driven wheelchair adapted with a splint and elastic bands. Their average speed on the tenth trial was about 0.1 m/sec. These results suggest that individuals with stroke could use bimanual wheelchair propulsion for mobility, both avoiding the problems associated with good-arm/good-leg propulsion and increasing the number of daily arm movements they achieve, which may improve arm movement recovery.**

I. Introduction

Although a key goal of early stroke rehabilitation is to help patients recover the ability to walk, stroke survivors often use manual wheelchairs during inpatient rehabilitation for seating and transportation because of initial difficulties with balance and walking [1-3]. Due to severe arm impairment, most of these patients must adopt an alternative strategy to operate a wheelchair, which is to pull forward with the unimpaired leg against the ground while operating the pushrim with the unimpaired arm [1,4].

The question of whether patients should use a wheelchair in such a fashion during their stay in a rehabilitation hospital is controversial [1,4-6]. On one hand, using a wheelchair grants mobility to patients who otherwise might spend their time between activities relegated to a fixed chair. This may motivate patients by facilitating socialization and enhancing their senses of freedom and self efficacy and might also exercise their spatial awareness [1]. On the other hand, using a wheelchair with the unimpaired hand and foot promotes disuse of the impaired arm, as well as an asymmetric posture that might lead to the development of abnormal tone and impede the recovery of walking ability later [5]. Providing early mobility with a wheelchair may also reduce a patient's motivation to recover walking ability [5].

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B. W. Smith (phone: 425-876-3049; e-mail: smithbw@uci.edu), D. K. Zondervan , D. J. Reinkensmeyer, V. Chan, and T. J. Lord are with the Departments of Mechanical and Aerospace Engineering and Anatomy and Neurobiology, University of California, Irvine, CA 92697 USA.

Here, we studied if individuals with stroke could use their severely impaired arm to power one wheel of a wheelchair that utilizes Lever Actuated Resonance Assistance (LARA). A LARA-based wheelchair allows patients to propel a manual wheelchair by pumping a lever in a resonant fashion as described in [7]. The lever is coupled to the wheel by a ratchet-like one-way clutch that translates forward pumps of the lever into forward motion of the chair. The lever is then elastically connected to the frame of the chair, creating a resonant system. Our prior analysis shows that operating a LARA-based wheelchair at resonant frequency could theoretically reduce the RMS torque required for sustained over-ground movement by upwards of 50% [7].

Our LARA-based device is an adaptation of the Resonating Arm Exerciser (RAE), a device designed for repetitive arm movement training after stroke [8]. RAE consists of a lever rigidly connected to one wheel of a wheelchair, a splint for attaching the impaired arm to the lever, and elastic bands between the lever and the frame of the chair, which makes the lever system resonant. To train with RAE, the user moves the arm to create forward and backwards rocking with zero net movement. Moving at the resonant frequency of RAE rewards the user with larger arm movements [8].

In pilot studies with RAE, stroke patients with severe arm impairment (upper extremity Fugl Meyer Scores below 15 out of 66) were able to start RAE rocking and were able to identify and move at the system's resonant frequency [8]. In addition, training repeatedly with RAE over three weeks reduced arm impairment. These findings suggested to us that such individuals might be able to ambulate over-ground with a lever drive wheelchair, and based on the motivational effect of mobility reported in [1], that such over-ground ambulation may help encourage arm movement practice.

The present study was a pilot study to assess the feasibility of having users with severe hemiparesis operate a bimanual LARA-based wheelchair. Specifically we asked: (1) How well can users with severe arm impairment propel themselves using the prototype chair? (2) How quickly can they learn to ambulate with the chair? (3) Does resonance assistance facilitate self-propulsion for these users?

II. Methods

A. Prototype LARA Wheelchair

We developed a prototype, bimanual, LARA-based wheelchair that operates in three modes (Fig. 1), which are selected using a custom, manual clutch mechanism (Fig. 2). The first mode is over-ground mode, which allows users to propel the wheelchair forward by pumping the levers. The second is a stationary mode in which the levers are directly coupled to the wheels of the chair to provide exercise in the form of assisted forward and backward rocking similar to RAE. The third is a decoupled mode that allows a caretaker to maneuver the chair from behind while the patient's arms are supported in a resting position. Each of the chair's levers has an arm support harness that attaches the user's forearm and hand to the lever. Each lever is coupled to the body of the chair by medical grade elastic bands, creating the resonant system that provides the assistance.

B. *Experiment*

Four stroke survivors (9, 27, 50 and 16 months post stroke) volunteered to participate in this experiment, which was approved by the Institutional Review Board of the University of California, Irvine. The subjects had severe arm impairment (upper extremity Fugl Meyer scores 21, 17, 16 and 15 respectively out of 66 points), rarely or never using their impaired arm in daily life, and could not grasp a wheelchair pushrim. Each subject was seated in the wheelchair and his or her contralesional (impaired) arm was secured in the chair's arm support using foam padding and Velcro straps. For each trial, subjects were instructed to propel the wheelchair 3.3 meters forward in a straight line using the wheelchair's over-ground mode. Yellow and black striped tape was fixed to the floor to define the desired straight line path. Each subject performed this self-propulsion task a total of five times in each of two wheelchair configurations, the order of which was randomized. The "with bands" configuration included the elastic bands that provide resonance assistance. The "without bands" configuration was identical to the "with bands" configuration, except the elastic bands were removed. Before each trial, the experimenter positioned the subject at the starting position by temporarily switching the chair into its decoupled mode and pulling them backwards. After each trial, the subjects were told the time it took them to finish the 3.3 meter movement and encouraged to beat their time. Following the five trials in each configuration, subjects' motivation and experience was assessed using the IMI (Intrinsic Motivation Inventory).

B. *Data Analysis*

Subjects' movement was measured using an active motion capture system (Phase Space) that recorded the positions of two LED indicators fixed to the frame of the wheelchair. Position was recorded at a rate of 100 Hz with a standard deviation in error of 0.025 meters (calculated as the standard deviation of the measured distance between the LEDs). Speed performance was derived from the position data as the average time required to travel one meter during each trial. This speed was computed by measuring the time required to reach a point three meters distant from the starting point (in a Euclidean sense) and then dividing by three meters. To exclude initial acceleration from the average speed calculation, the starting point was computed as the point where the chair had moved 0.1 meter from its position at the beginning of the trial. Euclidean distance was used to account for non-straight and off-center trajectories instead of using arc length, which would artificially reward winding paths. For trials where subjects stopped short of 3.3 meters, speed was averaged over the first 90% of the distance travelled from the starting point. For these calculations, the position of the chair was defined as the point centered between the main wheels on their axis of rotation.

Figure 1. The prototype bimanual LARA wheelchair features two identical levers, with arm support harnesses, coupled to the wheel of the chair with a one-way clutch and to the frame of the chair with elastic bands. This creates a resonant system to assist the user in propelling the chair forward.

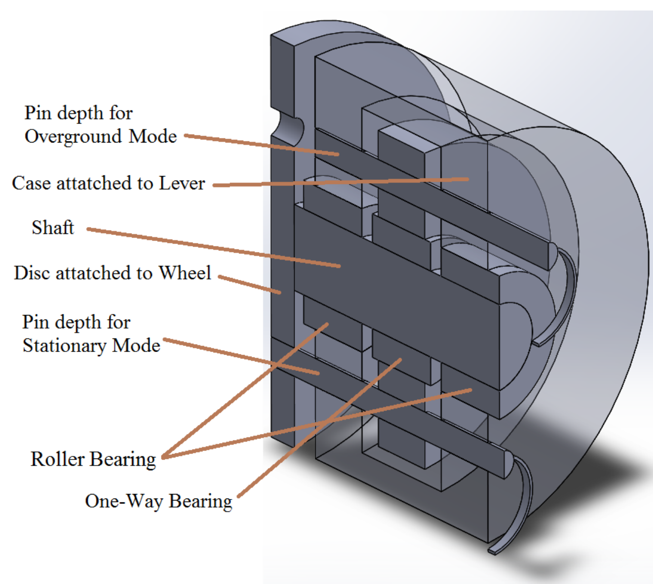

Figure 2. By adjusting the depth of two pins the one-way clutch mechanism can be set to operate in three different modes: (1) over-ground mode for self-propulsion; (2) stationary mode for exercise via back and forth rocking; and (3) decoupled mode (pins removed) for caregivers to maneuver the chair from behind while the patient's arm rests. The shaft is rigidly attached to the leftmost disc, and thus coupled to the wheel.

III. RESULTS

All four subjects were able to propel themselves using the prototype wheelchair in both the "with bands" and "without bands" configurations. The first subject initially required over 100 seconds to travel one meter, but increased in speed (significant linear trend with $p < 0.0001$) until on the 10th trial, she moved three meters in under one minute (Fig. 3a). She also initially veered to the left (the side of her impairment), but on just the 2^{nd} trial learned to coordinate her arms to move along a straight trajectory. The second and third subjects (right and left sided impairment respectively) both achieved straight trajectories on the first trial (Fig. 3b and Fig. 3c respectively). They exhibited no significant linear trend in speed across the 10 trials ($p = 0.11$ and $p = 0.49$ respectively) and had average speeds of 0.13 and 0.11 meters per second respectively. The fourth subject (left sided impairment) veered to the left on all 10 trials (Fig. 3d), but did increase his speed (significant linear trend with $p = 0.005$) as well as the distance he traveled before veering left, throughout the experiment. Averaging across the four subjects showed that there was a large but not statistically significant ($p = 0.19$) increase in the average movement speed from the first to the tenth trial (Fig. 4 left). Adding the elastic bands did not alter speed (Fig. 4 right).

Considering the survey responses to the IMI, subjects agreed with the statements "I put a lot of effort into this" (average response of 5.75 out of 7 which is significantly greater than a neutral response of 4, $p = 0.017$), "I tried very hard on this activity" (average of 6.38, $p = 0.0002$), and "I believe this activity could be of some value to me" (average of 6.38, $p = 0.00004$). Subjects disagreed with the statements "I felt very tense while doing this activity" (average of 2.25, $p = 0.002$) and "I was anxious while working on this task" (average of 1.75, $p = 0.003$). Opinions on other IMI questions were not significantly different from neutral.

IV. DISCUSSION

This experiment demonstrated that even stroke patients with severe arm impairment were able to propel themselves using a lever driven wheelchair designed with appropriate arm supports. Specifically they were able to apply sufficient power with their impaired arm to drive the chair forward, and they were able to coordinate the movements of their impaired and unimpaired arms to maintain a relatively straight over-ground path. The travel speeds were slow (~0.1 m/s), but are likely acceptable for moving in a hospital environment, especially if this movement is considered part of the rehabilitation activity for the arm. As for the rate of learning, two of the subjects immediately drove straight with good speed, and the other two rapidly improved their speed and straightness, indicating that learning to control the lever-drive chair was quick and intuitive.

To our knowledge, this is the first study to show that stroke patients with severe arm impairment can propel themselves in a manual wheelchair using an impaired limb to perform half of the work (without the aid of FES or foot pedal system as in [9]). Note that none of the subjects we tested could even grip a pushrim, much less propel a

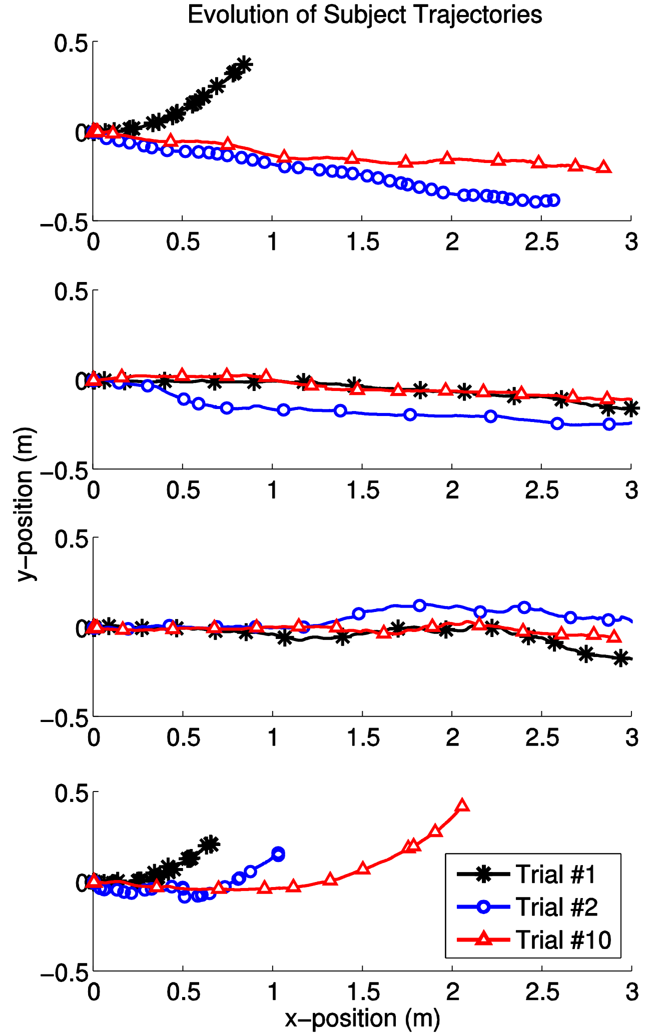

Figure 3. Overhead view of the trajectory of the wheelchair for four stroke subjects on their first, second and last (10^{th}) trial. Markers indicate position at two second intervals (five seconds for the first subject). A trial was ended if the subject veered too far to either side. From top to bottom, FM score (out of 66) and side of impairment (21L, 17R, 16L and 15L).

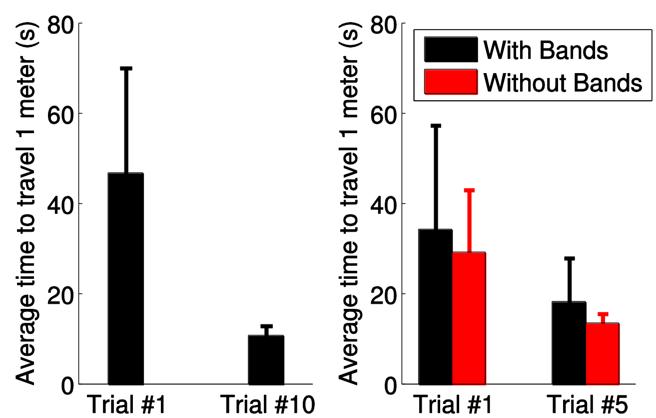

Figure 4. Left: On average, subjects increased their movement speed between the first and last trials of the experiment. Results are not statistically significant, likely due to the small sample size. Right: the speeds with bands were slightly slower, but again the difference was not significant. Error bars indicate the standard error of the mean.

wheelchair with one. We believe the propulsion observed in this study was possible because the prototype wheelchair: 1) simplified the movement task to one tractable by the subjects' limited coordination (i.e. pushing on a single degree of freedom lever); 2) supported their arms against gravity in a position that is apparently advantageous for the simple arm movement; and 3) removed the requirement to be able to grip and release the pushrim.

Based on our previous theoretical work [7], we hypothesized that resonance assistance would allow subjects to move faster by helping them achieve larger and faster arm movements. The results of this small pilot study did not provide evidence for this hypothesis but we observed that subjects most often did not move at resonant frequency. Our previous work with RAE showed that stroke patients are able to entrain to the resonant frequency of the stationary mode of the chair [8], but perhaps the over-ground movement task was more cognitively challenging and will require more practice to successfully entrain and obtain the potential efficiency benefits of resonance.

The elastic bands did provide other benefits. They created a neutral resting position for the arm near the middle of its range of motion. We observed that when using the chair without the bands, subjects tended to pump their impaired arm around a point further forward than they did their unimpaired arm, sometimes leaning forward or twisting their trunk toward their impaired arm. With the bands this imbalance was largely corrected. This improvement in symmetry might help prevent the development of asymmetric tone observed in [5]. Furthermore, unlike the widely used but debated good-arm/good-leg strategy for self-propulsion [1,4,5], the optimal strategy for using a bimanual LARA-based wheelchair involves symmetric movement. Continued practice and exercise may lead to increased symmetry.

We only tested here the ability of subjects to travel in a straight line 3 meters. Each subject easily did this 10 times, without signs of fatigue, suggesting trips of 30 meters in straight lines are easily achievable. Trips that require tight turns or backing up are not possible with the current design of the lever chair, as it cannot turn in place. For now, then, we see a compelling, first application of this approach for use by stroke in-patients who are receiving supervised rehabilitation therapy and must travel the straight hallways of most clinics to appointments and meals. This approach could greatly increase the amount of upper extremity movement repetitions they achieve, in a way that integrates naturally into their daily activities.

Subjects' responses to the IMI revealed that propelling the wheelchair felt effortful and required them to work hard, but that they were neither anxious nor tense during the task and believed their efforts were of value to themselves. These results suggest that the LARA-based wheelchair can provide stroke patients with a rigorous and meaningful yet tractable and comfortable exercise for their impaired arm. This ability to create meaningful movements with their impaired arm may motivate stroke patients to perform this exercise. Maintaining an individual's motivation to exercise may prevent the cycle of learned non-use of the impaired limb and thus lead to improved outcomes after rehabilitation. Subjects with the level of arm impairment of those enrolled in this study rarely or never use their arm during daily life.

V. Conclusion

Based on these pilot results, we hypothesize that a bimanual, LARA-based wheelchair could help meet some of the mobility needs of stroke survivors when they are inpatients, while avoiding dangers of early adoption of manual wheelchair use, which are encouraging disuse of the arm, passivity, and an asymmetric posture. We also hypothesize that such a device could direct a patient's desire for mobility into motivation to perform additional arm exercise meaningful for upper extremity rehabilitation. We have shown with RAE that such motions improve arm movement recovery [8] and similar wheelchair-based exercises have been reported to cause improvements in strength, endurance, flexibility and posture [10]. Within a rehabilitative framework, a LARA-based wheelchair could be introduced into a patient's lifestyle in such a way that it is viewed as an arm exercise and mobility tool, not a substitute for recovering walking ability.

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