Lever-actuated resonance assistance (LARA): A wheelchair-based method for upper extremity therapy and overground ambulation for people with severe arm impairment

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***Abstract*—People with severe arm impairment have limited technologies available for retraining their arms, and, if they also have difficulty walking, they often cannot effectively use a manual wheelchair because they cannot grasp and push the pushrim. We are using Lever-Actuated Resonance Assistance (LARA) to solve these problems. A LARA-based device can attach to a manual wheelchair and allow it to be used by people with severe arm weakness in a stationary exercise mode, or for self-powered overground ambulation. LARA uses a lever drive and arm support to appropriately position the arm and to reduce the dexterity required to operate the wheelchair. It also uses mechanical resonance implemented with elastic bands to provide assistance for both stationary exercise and overground ambulation. We first review here pilot results in which we used the LARA method to provide arm therapy to individuals with chronic stroke in stationary exercise mode. We then describe a novel motion-based user interface that allows individuals to control a video game with LARA while operating a wheelchair in resonance. Finally, for overground ambulation mode, we show in simulation that the mechanical resonance provided by LARA theoretically allows people with severe arm weakness to propel themselves with reduced effort and obtain speeds previously unattainable.**

I. INTRODUCTION

Therapeutic options for individuals with severe upper extremity (UE) impairment are currently limited. For example, such individuals are typically excluded from therapy paradigms such as constraint-induced movement due to generally poor outcomes, and have difficulty using equipment such as hand cycles or weight machines. Current robotic therapy devices are effective [1] but too expensive for widespread use.

Many individuals with severe UE impairment also have lower extremity impairment which necessitates use of a wheelchair for ambulation. Hand and arm weakness and discoordination, however, severely hamper use of a manual wheelchair. Individuals in this situation (e.g. ~80% of subacute stroke patients) ambulate in manual wheelchairs using their feet and/or less affected arm, which is awkward and does not contribute to recovery of the UE. Alternatively, they may resort to a powered wheelchair which does not provide for UE training in addition to being expensive and heavy. Failing to train the UE can lead to a cycle of learned disuse and decreasing functional ability [2], [3]. Pushrim-activated power-assist wheelchairs (PAPAWs) help people with arm weakness better use a manual wheelchair and are successful products [4-7], but they cannot be used by people who cannot appropriately position the arms or grip and push the pushrim. If a device could assist severely weakened individuals in wheelchair propulsion, individuals could self-train their arm as they moved about, much as current manual wheelchair users train their UE to high levels of fitness in the normal course of daily activity.

In order to address these needs, we are developing a novel approach to incorporating a lever drive for a manual wheelchair that allows the chair to be used in a stationary mode for UE exercise or in an overground mode for self-powered ambulation. The approach, Lever-Actuated Resonance Assistance (LARA), uses a splint and lever drive system to appropriately position the UE, and elastic bands attached from the lever to the wheelchair frame to create a mechanically resonant system that can assist in arm movement. Here we assess the performance of a LARA based device where assistance is purely passive. In practice robotic actuators could be used in series with the elastic bands to provide additional assistance in driving the lever. In the stationary training mode, the users roll themselves back and forth with the lever to exercise the arm. In the overground mode, users perform similar arm movements with the lever, but a ratcheting gear system translates this movement into net forward motion of the wheelchair. LARA provides many advantages to potential users with arm impairment over alternative methods for self-ambulation (e.g. powered wheelchairs or walking a manual wheelchair with their feet), such as a more ergonomic positioning of the arm that could prevent soreness or contracture, greater feelings of self efficacy, more efficient ambulation, and the ability to train their arm with active assistance in a safe manner without the aid of a caregiver. Clinicians would also benefit from the use of the device since it frees them from having to push patients in their wheelchairs from room to room and could permit more unsupervised therapy, allowing them to create more flexible training programs.

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We review here pilot results in which we used the LARA method to provide arm exercise to individuals with chronic stroke. We then describe a motion-based user interface for LARA-based devices that allows individuals to control a video game while operating in resonance during stationary training mode. For the overground mode, we show here that the LARA method can theoretically assist in ambulation by reducing the amount of applied force required to propel the wheelchair.

II. Pilot testing with RAE

The conceptual framework for LARA came from a predicate device we developed called the Resonating Arm Exerciser (RAE) for rehabilitation exercise of the UE in a manual wheelchair. RAE consists of a lever coupled directly to the wheel of a wheelchair with elastic bands stretched in tension between the lever and the frame (Fig. 1). Users operate RAE by pushing and pulling on the lever to "rock"

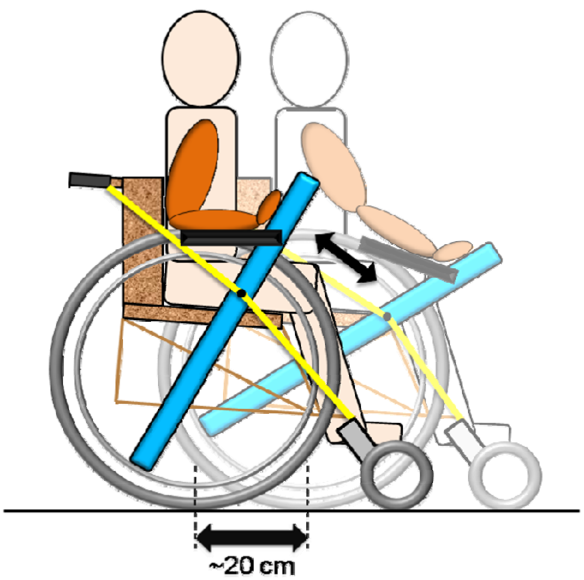

Fig. 1. A schematic drawing of RAE. A user can "rock" with RAE by pushing rhythmically on the lever in the parasagittal plane, rolling the wheelchair about 20 cm back and forth on the floor at its resonant frequency.

(or, more specifically, to roll back and forth with an amplitude of about 20 cm) in their wheelchairs, thus exercising their arms. We found that this system can be accurately modeled as an underdamped mass-spring-damper system with a resonant frequency of ~1 Hz [8]. Therefore, if a user rocks with RAE at the resonant frequency of the system, their active range of motion (AROM) of arm movement will increase. We verified this in a small pilot study; 6 participants with chronic stroke intuitively found the resonant frequency of the system when we asked them to rock with RAE, and their active range of motion (defined as the maximum angle change of the lever from flexion to extension) increased significantly by a factor of 1.7 when compared to a single push and pull on the lever without rocking, a significant increase ($p = 0.04$).

In a pilot therapeutic study of RAE, 8 volunteers with severe UE impairment due to chronic stroke showed significant improvements in both their AROM in RAE (66% ± 20% increase, $p = 0.003$) and their UE Fugl-Meyer scores (8.5 ± 4 pts increase, $p = 0.009$, starting UE Fugl-Meyer score was 17 ± 8 out of 66) after eight 45-minute exercise sessions with the device [8]. These improvements were sustained at a 3 week follow-up.

Exercising with RAE is an example of Lever-Actuated Resonance Assistance (LARA), which can be used to provide high repetition, goal-oriented, active-assisted rehabilitation for the UE. However, while the rhythmic rolling motion experienced during this LARA-based exercise is pleasurable, it can also be monotonous. Because of this, we sought to improve the stationary exercise mode by developing a motion-based user interface that would allow an individual to play video games while using a LARA-based device.

The results with RAE also showed that individuals with severe arm impairment, when appropriately positioned, could generate enough force to move a wheelchair back and forth. This suggested the possibility that LARA could be used to assist people with severe arm weakness in achieving overground ambulation with appropriate design. Therefore, we also performed detailed simulations of overground ambulation with LARA in order to determine the theoretical forces required for operation and speeds attainable both with and without resonance assistance.

III. Methods

A. Motion-based computer gaming interface for LARA

In order to receive resonance assistance from LARA during stationary exercise, a user must continuously rock at the resonant frequency of the device. We therefore asked the question "Can a novel user interface be designed that allows an individual to interact with a computer game in an intuitive way while performing continuous rhythmic movements at a constant frequency?" The design of this user interface is not trivial, since requiring users to move at a constant frequency only allows them to modulate a single degree of freedom: their movement amplitude. All but the most basic video games require at least two degrees of freedom to operate (i.e. moving up/down and left/right, or moving and pressing a button at the same time). We therefore developed a motion-based interface in which users interact with a virtual partner in order to move a cursor through two degrees of freedom in virtual space. In this system, users control the speed of the right side of the cursor by modulating the amplitude of their movement achieved with LARA. The virtual partner controls the speed of the left side of the cursor, which we held constant in the pilot experiment presented here. Thus, if a user rocks in a LARA device with a large amplitude, the cursor will turn to the left; if the user rocks with a small amplitude (or stops rocking entirely), the cursor will turn to the right. The cursor will move in a straight line if the user matches their amplitude to the speed of their virtual partner.

We tested how quickly and effectively new users could learn to use this motion-based user interface by asking 6 nonimpaired subjects to move a virtual cursor from a central position to a randomly selected target in one of eight equally spaced directions 50 times (i.e. 50 trials) by modulating their amplitude during rocking in RAE (Fig. 2). The subjects gave informed consent according to the standards set by the UCI Institutional Review Board. They were verbally instructed on how to control the cursor using LARA, but were not allowed to practice with the device before performing the experiment. We assumed the subject's movement would be sinusoidal at approximately the resonant frequency of the device based on earlier experiments with RAE, and thus were able to calculate the instantaneous amplitude, A, of the lever movement as:

$$A = \sqrt{\theta^2 + \left(\frac{\dot{\theta}}{\omega}\right)^2} \qquad (1)$$

where θ is the angular position of the lever (measured using a tilt sensor at 1000 Hz), $\dot{\theta}$ is the discrete derivative of the angular position, and ω is the estimated instantaneous frequency of movement calculated using a FFT algorithm in Simulink. The primary outcome measure for this study was the amount of time it took for the subjects to reach each target. The subjects were allowed 20 seconds to reach the targets; if they did not reach the target, we recorded their time for that target as 20 seconds and marked the trial as a failure.

B. Simulation of Overground Ambulation with LARA

We also created a model to simulate the performance of LARA for overground ambulation, allowing us to compare performance both with and without the elastic bands that provide resonance assistance. In order to simplify the simulation, we assumed that the lever drive transmission could be designed such that both pushing and pulling on the lever would transfer into a forward force on the coupled wheel. Transmissions such as this have been developed before for unassisted lever-driven wheelchairs [9]. When the lever drive is engaged (i.e. during acceleration), the model represents the device and user as a mass-spring-damper system with coulomb friction (Fig. 3a). When the lever drive is not engaged (i.e. during coasting), the model divides into two separate systems: a mass-spring-damper system with a reduced mass and damping that represents the user's arm and the lever, and a mass-damper system with coulomb friction that represents the coasting chair and user's body (Fig. 3b). Since the simulation switches between two linear systems, the overall system is nonlinear. Values for the simulation parameters and descriptions of what they model are displayed in Table 1.

To determine the benefits of resonance assistance we compared the performance of this model of wheelchair propulsion with and without the elastic bands. We quantified performance as the RMS torque input required to maintain a desired cruising speed. Metabolic energy consumption is roughly proportional to force output [10], [11]. We assumed that the user would produce a sinusoidal torque input when

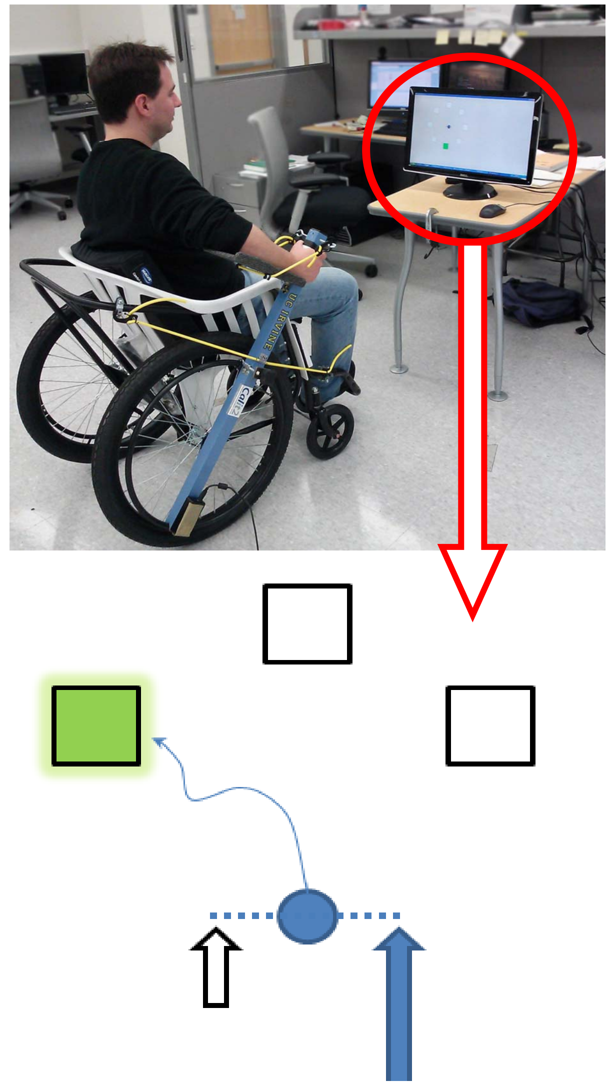

Fig. 2. Experimental Setup. Subjects attempt to guide the cursor into the target (highlighted green) by modulating their rocking amplitude in RAE. The left side of the cursor is always moving forward at a constant speed (shown with the clear arrow below), while the speed of right side increases with increasing amplitude (shown with the shaded arrow). Thus, a large amplitude will turn the cursor left, while a small amplitude will cause the cursor to veer to the right.

elastic bands were included, capitalizing on the system's resonance. This assumption is supported by previous studies with RAE in which we found that both unimpaired users and users with severe arm impairments after stroke naturally and quickly found the resonant frequency of RAE and produce a sinusoidal torque to sustain rocking at that frequency. When the elastic bands were removed from the simulation, we assumed that users would apply the optimal control strategy: bang-bang control. In this strategy, the user pushes as hard as possible to accelerate the lever, then pulls as hard as possible to decelerate the lever, completing a single pump of the lever, followed by coasting until another pump is required to maintain an average speed. This strategy is optimal in the sense that it minimizes the RMS torque required to maintain a

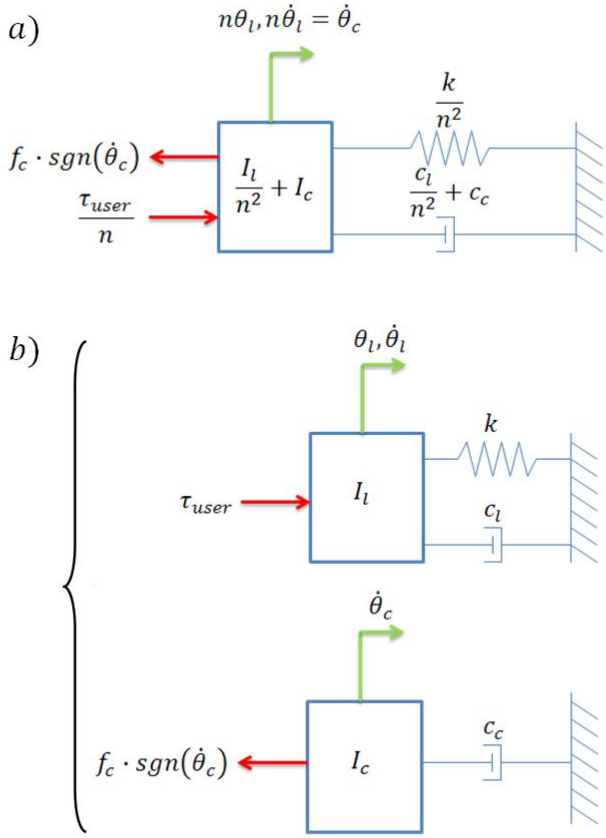

Fig. 3. Model of LARA in overground mode. The model switches between two states depending on whether the ratcheting mechanism is engaged (a) or disengaged (b). Friction of the wheel and gearbox is modeled with both a constant and velocity dependent term. The gearbox creates a gear ratio of n between the lever and wheel systems, which impacts the relative contribution of terms from these two systems in the combined system.

constant speed. We hypothesized that resonance assistance (i.e. including the elastic band) would allow the user to maintain target cruising speeds with smaller RMS torque inputs as compared to the optimal control scheme without resonance assistance.

The model has two adjustable parameters: the gear ratio between the lever drive and the wheels and the stiffness of the elastic bands. These parameters are uniquely defined by minimizing RMS torque, given the feasible frequencies and amplitudes of lever oscillation as well as the desired cruising speed of the wheelchair. We defined the natural frequency of the nonlinear system as the frequency of sinusoidal input that requires the minimal RMS torque to maintain a desired cruising speed. This natural frequency is velocity dependent because it depends on the pattern with which the lever drive is engaged with the wheel. Thus to compare performance at different cruising speeds, we tuned the simulated LARA device for optimal operation at each speed. In practice we would assess the cruising speed appropriate for the user of LARA and design the gear ratio and elastic band stiffness range of speeds, but it will operate optimally at the speed at which the user is most likely to cruise. When the bands were removed in the simulation, we tuned the system similarly by

TABLE I. SIMULATION PARAMETER VALUES

Symbol	Description	Value
θ_l	Lever angle from equilibrium	varies
$\dot{\theta}_c$	Angular velocity of chair wheel	varies
I_l	Inertia of lever and user's arm	2.5 $kg\ m^2$
I_c	Inertia of chair wheel; mass of chair and user	6.3 $kg\ m^2$
k	Elastic band stiffness	Varies
c_l	Damping of user's arm in lever	0.5 $Nm\ s$
c_c	Damping due to wheel and gear friction	0.05 $Nm\ s$
f_c	Coulomb Friction	0.1 Nm
τ_{user}	Torque applied to the lever	Varies
n	Gear Ratio	Varies

selecting the gear ratio that minimized RMS torque to maintain the desired cruising velocity.

We performed simulations using the model in order to compare performance with and without the elastic bands at two desired cruising speeds, 0.3 and 0.6 m/s. We selected these relatively slow speeds because they are appropriate for indoor environments. We set the natural frequency to 0.75 Hz and the maximum amplitude of lever movement to 40 degrees peak to peak, which are physiological plausible values. We achieved these parameters by setting the torsional spring constant to 57.8 and 63.4 Nm/radian for the two speeds respectively and the gear ratios to 0.70 and 1.43 with the elastic bands and 1.45 and 2.00 without the elastic bands respectively (here a gear ratio of 2.00 denotes that the wheel moves with twice the angular velocity of the lever).

IV. RESULTS

A. Motion-based computer gaming interface for LARA

To test whether it is feasible to control video games with two degrees of freedom within the LARA framework, we measured the time it took subjects (n = 6) to move a cursor into a target by modulating their sinusoidal movement amplitude during resonant rocking. We found that subjects were able to reach the targets consistently, and that they improved their performance over time (Fig. 4). The percentage of successful trials increased from 40% +/- 28% during the first five trials to 81% +/- 13% during the last five of the 50 total trials, a significant increase ($p = 0.018$). Subjects had more difficulty learning to steer the cursor to targets on the right half of the screen.

B. Simulation of Overground Ambulation with LARA

We also simulated overground ambulation with LARA and compared it to lever-driven ambulation without resonance assistance, estimating the forces required to operate the device at various speeds in both conditions. We

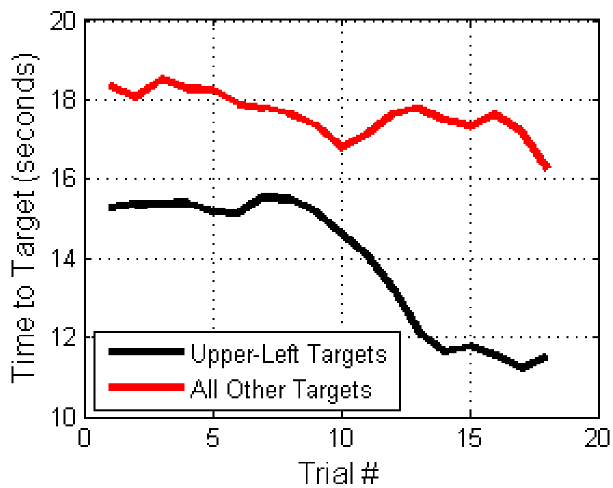

Fig. 4. A running average of the time to target for 5 subsequent trials, averaged across all 6 subjects. Subjects rapidly improved the ability to control the cursor while experiencing LARA, and better learned to steer the cursor towards the targets in the upper-left quadrant of the screen.

expect that the individuals with stroke-induced arm impairment who are candidates to use LARA will be able to produce maximum lever torques of approximately 15 to 25 Nm [12]. In this range, resonance assistance reduced the RMS torque necessary to maintain cruising speeds of 0.3 and 0.6 m/s by between 39% and 58% (Fig. 5). Furthermore, simulated users achieved comparable accelerations with and without resonance assistance (Fig. 6).

V. Discussion

Lever-Actuated, Resonance Assistance (LARA) provides a way to aid people with severe arm weakness in exercising their arms, and, potentially, in achieving self-powered overground propulsion. We have developed a unique, two degree of freedom motion-based user interface consistent with LARA that individuals can use to interact with a virtual environment or play video games, a common addition for many exercise devices in order to increase motivation and adherence [13], [14]. We showed here that healthy individuals can learn to use this user interface relatively quickly in order to move a cursor to a desired location. We also observed that subjects better learned how to reach targets located in the upper-left quadrant of the screen. This is likely an artifact of the experimental protocol, since the cursor began each trial oriented towards the top of the screen. Thus, if a subject were already rocking with a large amplitude when the trial began, the cursor would immediately be propelled into the upper-left quadrant. Subjects then had to turn the cursor and move a further distance if their goal target was not located in the upper-left quadrant for that trial. Although we did not measure it directly, subjects reported that playing the simple game we used in our protocol with the LARA-based user interface was both challenging and enjoyable, and they were engaged in the task for all 50 trials. We plan to test the system with individuals with UE impairment in the future so that we may calibrate the system to their specific needs.

We also presented evidence from simulations that LARA

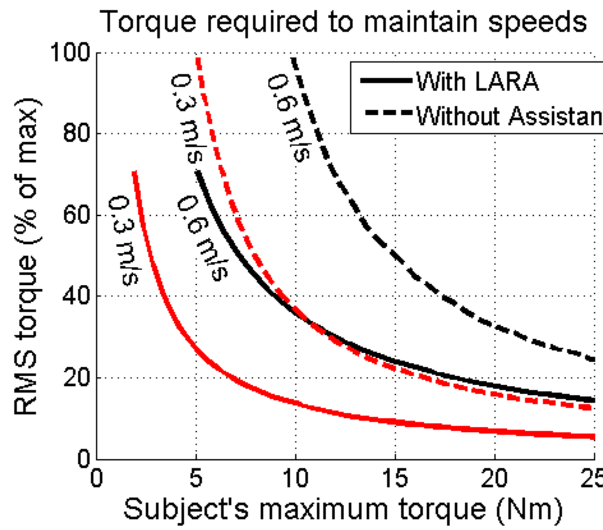

Fig. 5. RMS torque required to maintain target overground speeds both with and without the elastic bands that apply resonance assistance. In the "with LARA" case, the user produces an RMS torque that is at most 71% of the user's maximum torque because the torque input is sinusoidal. In this case, the user uses the minimal torque needed to maintain the target speed regardless of their strength. In the "without assistance" cases, the user uses a bang-bang-coast control scheme, producing push and pull torques at the user's maximum level. Persons with a severely impaired arm after stroke can generate maximum torques of between 15 and 25 Nm.

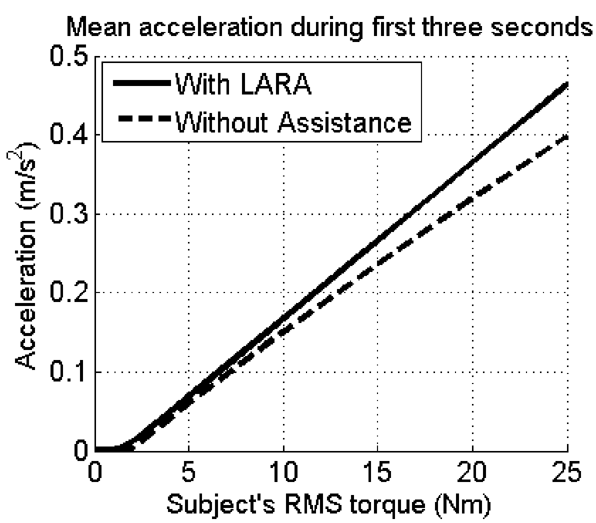

Fig. 6. Mean acceleration during the first three seconds from rest to 0.6 ms/s for the device with and without resonance assistance.

reduces the RMS torque needed to drive a wheelchair at two different cruising speeds representative of indoor wheelchair operation. LARA simplifies the strategy for operating a wheelchair, since it simply requires the application of a sinusoidal torque input at the resonant frequency rather than bang-bang control. We know from previous work with RAE that even individuals with severe, stroke-induced arm impairment can naturally and quickly drive a LARA-based device at its resonant frequency. The anticipated candidates for LARA will need roughly half the RMS torque to propel themselves at constant indoor speeds when resonance assistance is applied. Individuals with even greater arm weakness (between 5 and 15 Nm) will see even larger reductions in required torque and achieve higher speeds than would be possible without the resonance assistance.

Individuals with greater arm strength than the anticipated candidates, although likely able to operate a lever driven wheelchair without resonance assistance, would still benefit from the simplified control scheme it allows (a single degree of freedom movement, as opposed to the complicated arm motions necessary to drive a push rim wheelchair) as well as the improved positioning of the hand and arm. Furthermore, without elastic bands, the user is required to stop the motion of the lever after each arm pump. If the user does not time this deceleration properly, the lever will apply an undesirable torque to the shoulder as it reaches the limit of its range of motion, which might cause undue wear on that joint. With resonance assistance, the elastic bands provide this deceleration and maintain a safe range of motion for the arm.

We have also shown that resonance assistance does not impede acceleration from rest, an important measure given that wheelchair operation requires regular stop and go motion around corners and through doors. Furthermore, resonance assistance allows users to perform these low speed maneuvers and accelerate back up to speed using a simple sinusoidal control scheme, and once up to speed it substantially reduces the energy they expend while cruising. Therapeutically, we expect that many users who are rehabilitating from stroke will benefit from the increased repetition of arm movement that comes from ambulating with LARA. This rehabilitation approach has the added benefit of training an activity of daily living if these users have a LARA-based device in their home.

Our next steps in the development of LARA are to build an initial prototype LARA-based device for overground ambulation and to design a robotic clutch and braking mechanism actuated by a force sensor in the lever handle to allow individuals with only trace levels of grip strength to brake and reverse directions with the device. This second step is especially important since braking in a manual wheelchair is often used as part of a turning strategy and is also important for navigating on sloped terrain. By allowing braking to be controlled by a grip sensor, we aim to allow severely impaired individuals to safely and effectively maneuver with LARA.

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