Title

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There is plenty of room for motor learning at the bottom of the Fugl-Meyer:

Acquisition of a novel bimanual wheelchair skill after chronic stroke using an unmasking technology

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Abstract

Many people with a stroke have a severely paretic arm, and it is often assumed that they are unable to learn novel, skilled behaviors that incorporate use of that arm. Here, we show that a group of people with chronic stroke (n = 5, upper extremity Fugl-Meyer scores: 31, 30, 26, 22, 8) learned to use their impaired arm to propel a novel, yoked-clutch lever drive wheelchair. Over six daily training sessions, each involving about 134 training movements with their “useless” arm, the users gradually achieved a 3-fold increase in wheelchair speed on average, with a 4–6 fold increase for three of the participants. They did this by learning a bimanual skill: pushing the levers with both arms while activating the yoked-clutches at the right time with their ipsilesional (i.e. “good”) hand to propel the wheelchair forward. They perceived the task as highly motivating and useful. The speed improvements exceeded a 1.5-factor improvement observed when young, unimpaired users learned to propel the chair. The learning rate also exceeded a sample of learning rates from a variety of classic learning studies. These results suggest that appropriately-designed assistive technologies (or “unmasking technologies - UTs”) can unleash a powerful, latent ability for motor learning even for severely paretic arms. While UTs may not reduce clinical impairment, they may facilitate large improvements in a specific functional ability.

I. Introduction

Stroke is a leading cause of disability in the United States with nearly 800,000 people experiencing a stroke each year [1]. Approximately half of people who have a stroke end up with severe arm impairment [1]. Arm impairment can be reduced with intensive rehabilitation, such as what is made possible with robotic therapy devices, but the average improvement is small [2]. Further, arm movement recovery, measured as change in the upper extremity Fugl-Meyer (UEFM) score over time, follows a well-defined trajectory for most patients, which is predictable from early EUFM score [3], [4]. The small improvements in

EUFM score observed with intensive therapy coupled with the predictable progression of this score suggests limited use-dependent motor plasticity after stroke [5] – that is, a relative inability to alter limb impairment fate through training.

This raises the question, “How much motor learning is possible with a severely impaired limb?” Here, we studied this question using a novel lever-drive wheelchair called “LARA” or “Lever-Actuated Rehabilitation and Ambulation,” that requires coordinated bimanual activity to be propelled. In a previous pilot study with a stationary version of LARA, a device called RAE, we found that users with severe arm impairment (FM score = 21.4 points ± 8.8 SD out of 66) could move the levers and synchronize to the resonance of the device, created by springs attached to the levers, and that repeatedly moving the levers had a therapeutic benefit [6], [7]. We then made RAE into LARA by incorporating one-way bearings into the levers and found that people with severe arm impairment could also drive LARA overground [8], [9]. This is important clinically because it means that stroke inpatients could potentially bimanually propel their wheelchairs, greatly increasing their arm activity beyond the low amounts that are typical during routine therapy [10], and thus potentially enhancing use-dependent plasticity [11].

With this clinical application in view, a practical problem with the first version of LARA was that it had limited maneuverability because the user could not back-up or spin in place, which would make it difficult to use for transportation in a rehabilitation unit. Thus, for the present study, we developed a second version of LARA with a novel drive system we call “yoked hand clutching” [12] (Fig. 1). Yoked hand clutching requires users to grip a single clutch handle with their ipsilesional (i.e. “good”) hand that simultaneously actuates both clutches: one on the left and one on the right, which attach the push levers to their respective wheelchair wheel. Somewhat counterintuitively, users can use this system to turn in place and back up by timing the pumping motion of the two levers with clutching by the good hand [12].

Learning to time the bimanual pumping and unimanual clutching is a motor skill that requires practice. Here, we studied how long it took people with severe arm impairment to learn this skill and thereby improve their speed of overground travel around a figure eight course using LARA.

II. Methods

A. Experimental Protocol

Five volunteers (Table 1), four males and one female, (mean age = 61.6 years ± 6.1 SD) with chronic stroke (1–3.6 years post-stroke) and severe arm impairment (mean EUFM score = 23.4 points ± 9.3 SD) provided informed consent to participate in this experiment, which was approved by the U.C. Irvine Institutional Review Board.

In this motor learning experiment, we were interested in skill improvement, measured as driving speed, as the primary outcome, but we also recorded clinical assessments as secondary measures as described below. Participants navigated a figure eight track with a 14 m long path designated with masking tape on the floor. This was an identical protocol to previous study with younger, unimpaired participants [12]. To match practice times with that previous study (in which participants completed a fixed number of laps each session rather than a fixed training duration like this study), participants practiced for the following number of minutes each session for six training days spaced over two weeks: Session 1: 5 min 37 sec; Session 2: 4 min 22 sec; Session 3: 4 min 1 sec, Session 4: 3 min 42 sec; Session 5: 3 min 35 sec; Session 6: 3 min 21 sec. This reduction in practice reflected the previous study's participants increase in speed.

Participants' lap times were recorded with a stopwatch, with each new lap beginning when participants crossed tick marks on the track, which were spaced to be a quarter of the total track distance. A chest heart rate belt (Blu Beets Bluetooth Wireless Heartrate Monitor) was worn during the study to measure resting and peak heart rates. Resting heart rate was taken before the experiment began just after the participant had settled in the chair, and peak heart rate was measured while driving through the course. Gyroscopes (MPU 9250) attached to each lever recorded data at 5 Hz on a microcontroller (Arduino M0 board with AnyCubic Data Logging Shield).

The UEFM and Box and Block Tests were evaluated by an experienced physical therapist before Sessions 1 and 6. Motivation was evaluated using the Intrinsic Motivation Inventory (IMI) after each session [13]. Limb spasticity was evaluated for the shoulder, elbow, wrist and hand by the Modified Ashworth (MAS) before and after each session and a mean score was reported as the average of these four. Before and after each session pain was evaluated with the Visual Analog of Pain Scale (VAPS). Use and ease of use of the impaired limb outside of training was evaluated during Session 1 and 6 by self-reported Motor Activity Logs (MAL).

B. Data Analysis

The average speed was determined by dividing the number of laps completed by the amount of time required to complete them. The gyroscope data was analyzed in terms of peak lever speed on each pump, instantaneous pumping frequency and instantaneous pumping synchrony. To identify lever pumps, the MATLAB function "findpeaks" was used with the threshold option of "MinPeakProminence". Threshold levels were tuned manually for each subject. The peak lever speeds were found as the peak value identified by "findpeaks". The instantaneous pumping frequency was calculated as the inverse of the time difference between peaks. The pumping synchrony, a measure of bimanual coordination advantageous for forward propulsion, was determined by performing a zero-lag cross-correlation between the unimpaired and impaired side gyroscope data with a window of 10 samples centered at each peak location of the unimpaired side gyroscope data.

Due to an error with the memory card, all gyroscope data was lost for Sessions 1 and 2, and two subjects did not have any gyroscope data recorded on Session 6, so for these participants their data from Session 5 was used for the Session 6 instead.

To compare learning rates with those from a sample of previously published learning experiments, MATLAB's "fit" function was used to fit power curves (curve fit option 'powerl') to the mean data of the five subjects over the six sessions with:

$$T = BN^{-\alpha}, \quad (1)$$

where T is the time to finish the task and N is the amount of trials, and B and α are constants. In particular, B is the baseline, i.e. the first trial's performance time and α is the learning rate [14]. This same equation was also fit to a previously collected dataset acquired from young, unimpaired adults (mean age = 22.3 ± 2.8 years, N = 11) who drove the same version of LARA with the same experimental protocol [12]. Statistical comparisons were carried out with the Friedman's test, Wilcoxon Rank Sum (WRKS) test and Wilcoxon Sign Rank (WSR) test.

III. RESULTS

A. Learning to drive the yoked clutch lever drive wheelchair

The participants significantly increased their mean speed over the six training sessions (Fig. 2, Friedman's test, $p < 0.001$). The average increase in speed was 305 % ± 197 SD, with three participants achieving an increase over 400% and two around 200%. The learning rate, estimated as the exponent of the power curve fit, was $\alpha = 0.62$ for the people with a stroke. This rate was twice that of the mean learning rate reported for a sample of classic learning experiments ($\alpha = 0.28 \pm 0.16$ SD; Fig. 3) [15]. The young unimpaired subjects who learned to drive LARA had a learning rate similar to that found in the classic experiments ($\alpha = 0.29$; Fig. 3).

B. Features of the lever movement

From Session 3 to 6 (the two sessions for which we obtained gyroscopic data from both levers) we found an increase of about 50% in wheelchair speed that neared significance (WSR test, $p = 0.06$). We plotted histograms of peak pump speed, pump frequency, and pump synchrony from this data, in order to gain insight into the mechanisms of speed improvement (Fig. 4).

First, it was clear from these graphs that there was substantial pumping activity by both limbs on both days (mean # of pumps = 124 ± 48 SD for the impaired and 156 ± 37 SD for the unimpaired limbs on Session 3, and 124 ± 44 SD for the impaired and 153 ± 25 SD for the unimpaired limbs on Session 6). The number of pumps was not significantly different between arms (WRKS test, $p > 0.16$), and did not change significantly for either arm from Session 3 to Session 6 (WRKS test, $p > 0.98$). As confirmed by video recordings of the sessions, many of these pumps did not move the chair, especially in the early sessions. That is, all participants struggled to coordinate the clutching with the lever movement, especially the slower participants, and performed many movements of the levers with the clutch "OFF", and thus these movements did not turn the wheels.

The peak pump speeds tended to be slower for the impaired limb (Fig. 4 top row); specifically, the impaired side was significantly slower in Session 3 for participants with EUFM score 31, 26 30 and 8, and in Session 6 for participants with EUFM score 31, 26, and 8 (WRKS test, $p < 0.05$). The only participants that showed a significant change in peak pump speed from Session 3 to 6 were the participant with EUFM score 26, who showed a significant increase in his unimpaired arm pump speed (WRKS test, $p = 0.02$), and the participant with EUFM score 31, who, in contrast, showed a significant increase in his impaired arm pump speed (WRKS test, $p < 0.005$). Participants showed a preference for a pump frequency at or just below 1 Hz, and this frequency stayed roughly constant across Sessions 3 and 6 with no significant changes between arms or over Sessions for any participant (Fig. 4 middle row). Increases in pump speed or frequency do not seem to be able to explain the 50% increase in speed from Session 3 to 6.

In terms of pump synchrony (Fig. 4 bottom row), all participants showed predominantly positive correlations, concentrated at or above 0.5, indicating they tended to move the limbs in phase with each other. All participants altered their synchrony distribution with training, but the change was significant only for the participant with EUFM score 30 (WRKS test, $p = 0.04$). She increased her synchrony, as was the trend for three of the other participants. The fastest participant showed a different trend. He increased the percentage of pumps with zero synchrony - i.e. with one limb holding steady while the other limb pumped. From video analysis, it was clear that by Session 6 he had learned that he could drive the chair faster by pushing harder with his unimpaired arm, but that this caused steering error. To correct for the steering error, he used his impaired arm to hold one wheel still during a brief bout of backwards pumping with his unimpaired arm, correcting the orientation of the chair. This resulted in more zero correlation pumps.

In summary, we observed subtle changes, if any, in peak pump speed and frequency, and a trend toward more synchronous arm movement from Session 3 to 6. Based on this data, we speculate that it is the coordination changes and improvements in clutching (not observable from the gyroscopic data but apparent in the video recording), that primarily explain the 50% increase in speed. A rough indicator of clutching efficiency, given that peak pump speeds and frequencies stayed about the same, is distance travelled per pump of the impaired arm; this number increased from 0.18 m/pump ± 0.16 SD to 0.22 m/pump ± 0.14 SD from Session 3 to 6, a 22% increase that was not significant (WRKS test, $p = 1$).

C. Clinical, physiological, and motivational outcomes

Learning to drive the wheelchair had very little effect on the clinical arm impairment: from Session 1 to Session 6 participants increased their UEFM scores by 2.2 points ± 1.1 SD, an improvement that neared significance (WSR test, $p = 0.06$, Fig. 5A). Box and Blocks scores improved by 2.2 blocks ± 2.5 SD, a non-significant improvement (WSR test, $p = 0.3$, Fig. 5B).

We assessed the short-term physiological effect of exercise with LARA using a heart rate monitor. on average, the participants significantly increased their heart rate by 36 beats per minute (BPM) ± 10 SD while they drove the chair (Fig. 5C, measured on Session 6, WSR test, $p = 0.02$).

The IMI subscore for Competence increased significantly over the six training sessions (WSR test, $p < 0.05$), while the Effort and Usefulness subscores did not change (Fig. 5D). on a scale of 1 to 7 of the IMI, where 7 represented “very true” and 1 represented “not true at all", the participants scored the perceived usefulness/value of LARA as 6.8 points ± 0.4 SD, their perceived competence as 5.6 points ± 0.63 SD, and their perceived effort/importance as 5.8 points ± 2.2 SD, at the end of Session 6.

As assessed by the Visual Analog Pain Scale participants did not experience any pain or pain in Sessions 1 to 6 (mean VAPS score = 0 points ± 0 SD). Similarly, as assessed by the Modified Ashworth Score, upper limb spasticity did not change significantly from the post-Session 1 to the postsession 6 (MAS = 0 points ± 0.18; WRS test p = 1). There was also no significant change of limb spasticity within each session, (mean score pre-Session 1 = 1.75 ± 0.85 SD, mean score post-Session 1 = 1.7 points ± 0.82 SD, mean score preSession 6 = 1.8 points ± 0.89 SD, mean score post-Session 6 = 1.7 points ± 0.78 SD, WRS test p = 0.98, p = 0.85).

By the end of Session 6 participants increased their Motor Activity Log Amount of Use score to 1.2 ± 1, a non-significant improvement from the Session 1 score of 0.9 points ± 0.8 SD (WSR test, p = 0.55). Similarly, participants increased their MAL Quality of Use score to 1.3 points ± 0.9 SD, a nonsignificant improvement from the Session 1 score of 0.9 points ± 0.9 SD (WSR test, p = 0.69).

IV. Discussion and Conclusion

How much skill learning is possible with a severely impaired limb? In the context of the LARA assistive device, we believe it is apt to call the amount of learning we observed "massive". The learning rate, defined as the exponent in the power-law fit to the speed improvements, was two times greater than the learning rate exhibited for the same task by young, unimpaired participants. It was also two times greater than the learning rates identified in a wide variety of tasks studied in classic motor learning experiments. While this learning of a bimanual skill did not manifest as a substantial reduction in clinical impairment, it translated into a large improvement in function - here, the ability to bimanually propel a wheelchair. Participants rated themselves increasingly competent at driving LARA, and rated their new ability highly useful and valuable.

These results can be compared to the recent results from Hardwick et al. [5], in which participants with stroke learned to flex the elbow to a target. Participants were divided into unimpaired, mild, and moderate stroke groups. The moderate stroke group improved their speed-accuracy tradeoff through learning, enough to move them up a classification level – i.e. to the level of performance that the mild stroke group exhibited before further training – even though their impairment level, assessed clinically did not change. Thus, learning was possible, even to the extent that the arm looked more normal for a specific task, but it did not "transform" the overall impairment status of the arm.

The present study adds to this the finding that a much larger amount of learning is possible given the "right task". The functionally-meaningful and clear goal of propelling forward combined with the arm support that LARA provides are likely key factors here. Further, while it may not alter clinical impairment status of the arm, this learning can still be transformative because it can result in a new functional ability – here, the ability to bimanually propel a wheelchair. This is important for people with a stroke. By using LARA for wheelchair mobility, people can not only incorporate their “useless” arm into a meaningful task, but they can also greatly increase the amount of arm activity they experience throughout the normal course of the day. We hypothesize that this increased activity will improve long-term outcomes. In this context, LARA can be viewed as a dual assistive and rehabilitative device, an emerging paradigm in rehabilitation therapy.

The mechanism behind this massive learning was likely that participants became better at coordinating the arms with the hand-clutching. Future studies should instrument the hand clutch and wheelchair wheels as well as the levers to understand better the process of learning to drive LARA.

An interesting finding was that training with LARA for only a few minutes increased heart rate to the low end of the target exercise zone for the participants’ age group [16]. This suggests that LARA not only provides a platform for motor learning, but also a platform for cardiovascular exercise, which may promote health and fitness even in the early stages after stroke [17]. Likewise LARA did not increase spasticity or pain, making it a feasible exercise device for people with severe arm impairment.

These results suggest an important goal for future work in rehabilitation engineering: developing assistive technologies (ATs) that unmask the robust but latent motor learning ability that people with severe impairments still possess; we propose calling such ATs “Unmasking Technologies” (UTs). We hypothesize that there are many UTs still undiscovered, and that they can help people to achieve unexpected levels of function. It is not necessary that UTs do everything for the user; and indeed, such an approach may be counterproductive. For a UT, what matters most is not how well users do with it on the very first day, but, rather, how well they learn how to use it by exercising and improving their preserved abilities. There is plenty of room for learning even by the most impaired individuals.

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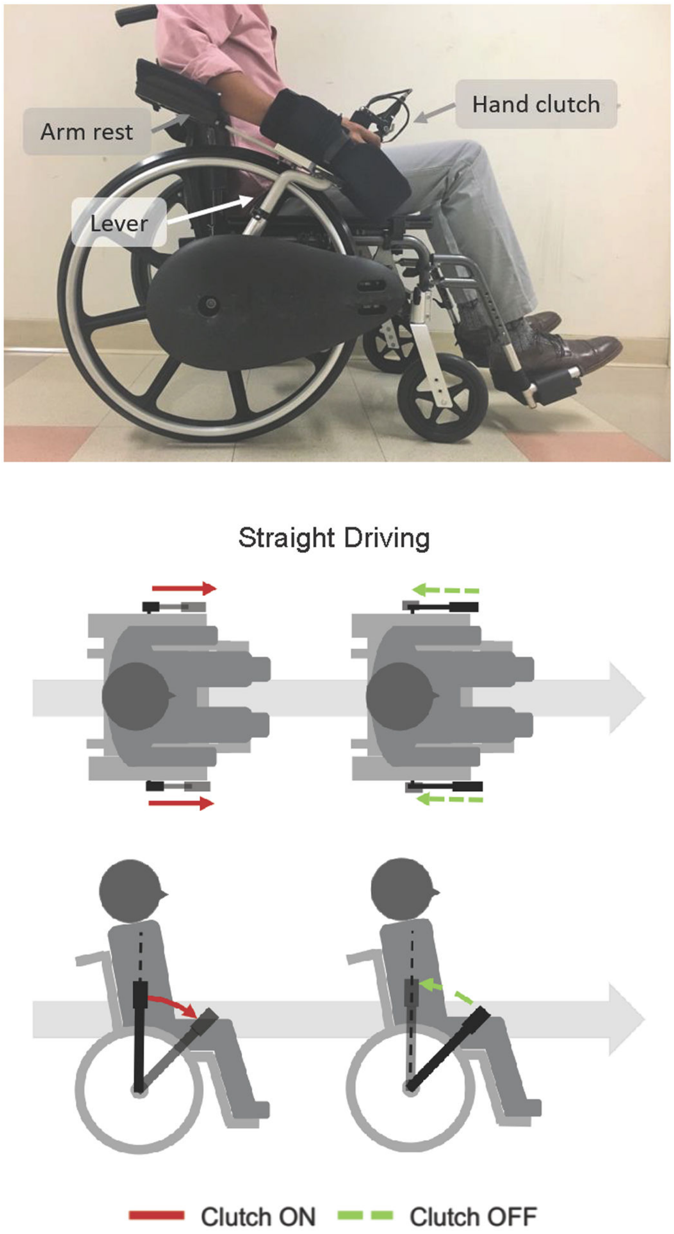

Figure 1.

The Yoked Hand-Clutch version of the LARA wheelchair. **Top**: When the user is not squeezing the hand clutch, the levers rotate freely around the axels without moving the wheels. When the user squeezes the hand clutch, both levers become attached to each wheel (i.e. the single “yoked” hand clutch activates both of the clutches between the levers and wheels on both sides), so moving the levers now turns the wheels. **Bottom**: Schematic drawing showing how to use the clutch to drive the LARA wheelchair in a straight line. The user activates the clutch (ON, red) when pushing the levers forward and releases it (OFF, green) when pulling the levers back. The user can turn or back up by changing the phasing of the single hand clutch relative the the two lever motions.

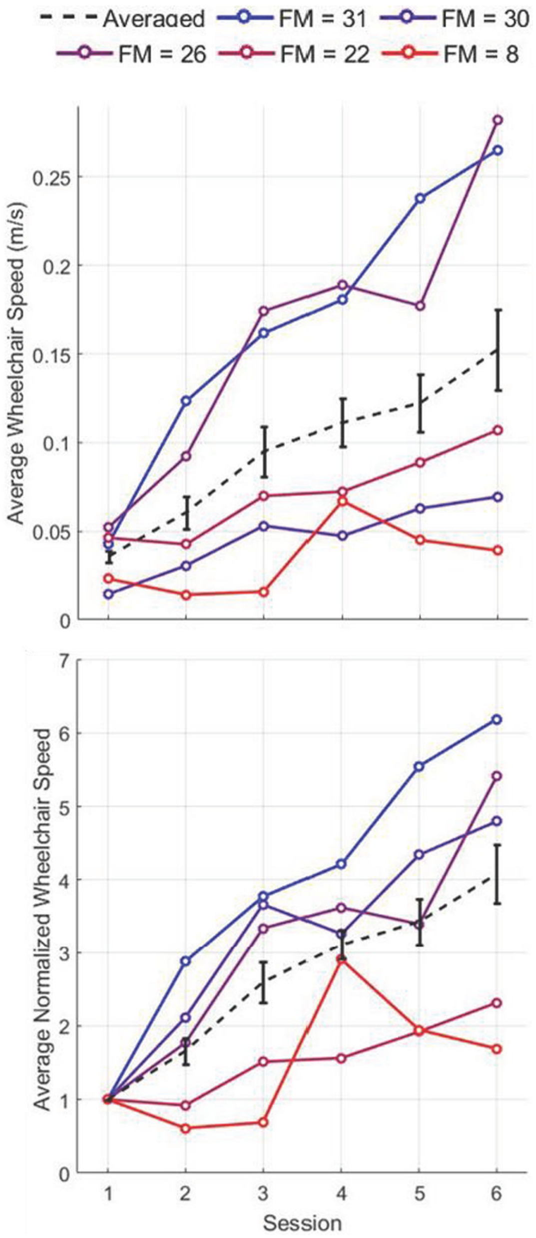

Figure 2.

Wheelchair speed across sessions. **Top**: Average wheelchair speeds of the five participants and average wheelchair speed of the group along the six sessions. The participants with stroke significantly increased their mean speed over the six sessions of the study (Friedman's test, $p < 0.001$). **Bottom**: Wheelchair speeds of the five participants normalized to speed in first session. Bars indicate standard error.

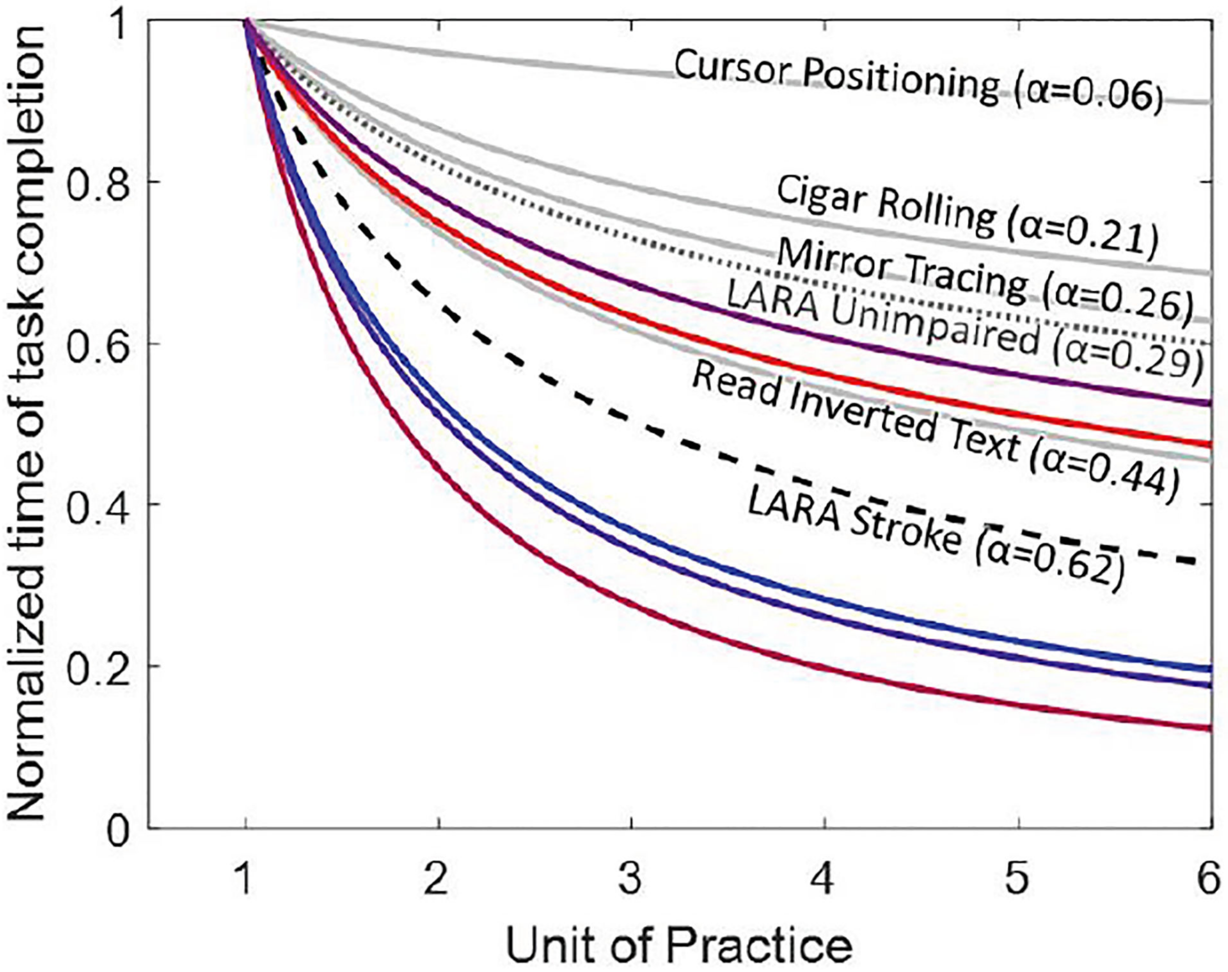

Figure 3.

Learning curve fits for LARA and from a variety of other motor learning studies. Four representative learning curves of twelve classic experiments [15] (grey) taken from together with average learning curves from impaired (black dashed) and nonimpaired participants (dark grey dashed) driving the LARA wheelchair, as well as the individual learning curves from impaired participants (red to blue). The y-axis is normalized to the time required to complete the task after one unit of practice. The x-axis is normalized to multiples of that unit of initial practice. The power curve fit took on a massive motor learning rate for the stroke participants. This rate is more than twice that of the mean learning rate reported for a sample of twelve classic learning experiments ($\alpha = 0.28 \pm 0.16$; Fig. 3). The rate for unimpaired participants was similar to this average. The learning rates for each subject from highest FM score to lowest: $\alpha = 0.91, 0.97, 0.36, 1.2, 0.41$ with R-Squared values: 0.75, 0.68, 0.43, 0.63, 0.86.

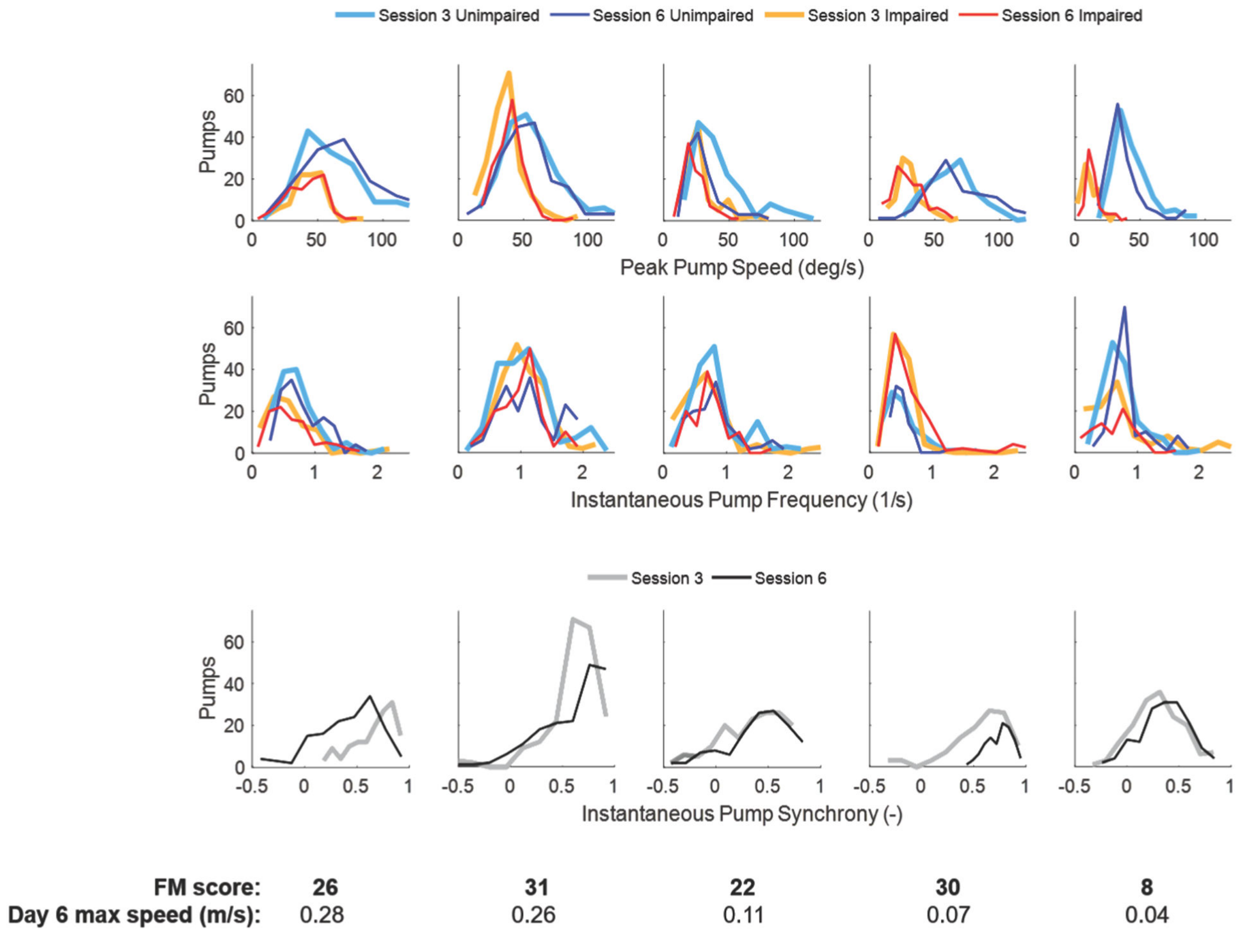

Figure 4.

Exploratory histograms derived from lever gyroscopes for the 5 participants with stroke on Session 3 and 6, across which their average speed increased 50%. **Top**: Peak pump speed for the impaired (red/orange) and unimpaired (blue/cyan) arms for Session 3 (dashed lines) and Session 6 (solid lines). **Middle**: Instantaneous pump frequency for the impaired (red/orange) and unimpaired (blue/cyan) arms for Session 3 (dashed lines) and Session 6 (solid lines). **Bottom**: Instantaneous pump synchrony between impaired and unimpaired arms for Session 3 (grey dashed lines) and Session 6 (black solid lines). Note that the graphs are ordered from left to right from fastest to slowest participant on Day 6.

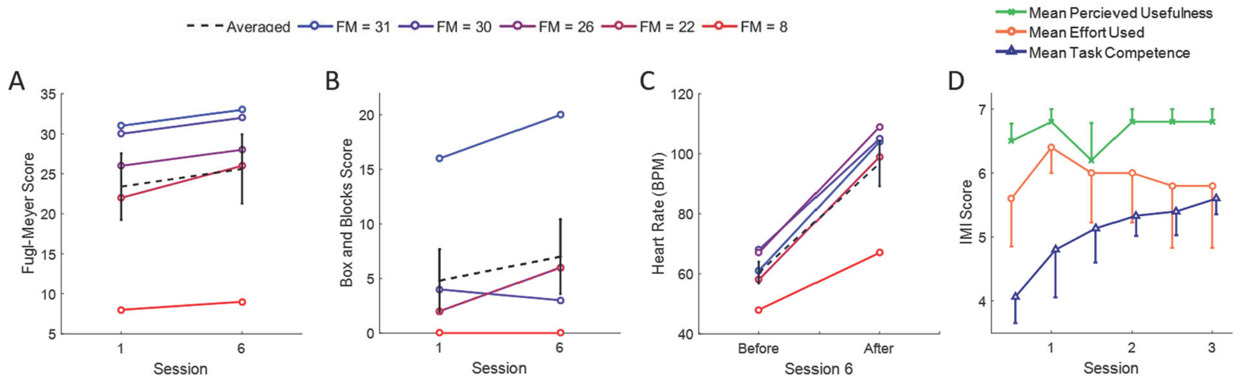

Figure 5.

Clinical and Physiological measures. **A**) Change in Box and Blocks scores between Sessions 1 and 6. Between the first and last session of training, there was an average improvement of 2.2 ± 2.5 SD blocks, a non-significant change (p = 0.1). The participantst with FM = 26 and FM = 22 both had Box and Blocks score of zero. **B)** Change in UEFM scores between sessions 1 and 6. Between the first and last session of training, there was an average improvement of 2.2 points ± 1.1 SD, a significant improvement (p = 0.01). **C)** Participants' heart rate increased by 36.4 BPM ± 10 SD while training with LARA on Session 6, a significant increase (p = 0.02). **D)** IMI subscore for Competence (triangles) increased significantly over the six training sessions (p < 0.05), while Effort (circles) and Usefulness (x's) scores did not change. Bars indicate standard error.

TABLE I.

Participants' Demographic and Clinical Information

FM Score	Age	Gender	Injury side	Preferred Arm	Type of Stroke	Days since stroke
31	62	M	R	R	H	439
26	53	M	R	R	I	469
22	59	M	L	R	H	1297
30	65	F	L	R	I	551
8	69	M	L	R	I	367

M: male, F: female, R: right, L: left, H: hemorrhagic, I: ischemic