# Remote monitoring and quantification of upper limb and hand function in chronic disability conditions

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## ABSTRACT

This paper describes a convenient, home-based telerehabilitation system designed to improve upper limb and hand function in adults with cerebral palsy. The training program incorporates a variety of computer-guided sensorimotor activities such as unilateral and bilateral reaching, reaching and grasping, object manipulation, and tactile discrimination tasks. Quantitative measures of performance are uploaded to the laboratory after each training session for further analysis. Webcam monitoring of performance occurs periodically throughout the training period. Twelve adults with cerebral palsy completed a 40 min/day, five days/week training program over eight weeks. Temporal measures of performance indicated significant improvement in reaching and hand manipulation ability as well as improved tactile discrimination. Preliminary analysis of the time course of change revealed variable patterns within and across participants. The capacity to measure change throughout a training program provides an opportunity to investigate how learning occurs over time in chronic disability. Compliance was excellent with subjective reports indicating improvement in activities of daily living. Future development includes a fully automated system with stand alone modules which allow for customization of training protocols depending upon specific needs of the user.

## 1. INTRODUCTION

Repetitive practice of goal-directed movements has been shown to improve function in individuals with chronic upper limb impairment such as stroke (Langan and van Donkelaar, 2008; Taub et al., 1998; Wolf et al., 2007) and cerebral palsy (Gordon et al., 2005, 2006; Qiu et al., 2009; Taub et al., 2007). Typically, movement-based therapy programs involve several hours a day of task-specific training in an outpatient setting and with therapist supervision. These constraints may be cost-prohibitive for many individuals and may represent serious barriers to compliance.

Major advances in telecommunications technology have the potential to provide more efficient and effective therapies for individuals with motor disabilities. While the application of telemedicine in rehabilitation is still limited, several studies have demonstrated the effectiveness of upper limb training programs delivered via the Internet for individuals with chronic upper limb motor impairments such as stroke (Carey et al., 2007; Deutsch et al., 2007; Holden et al., 2007; Page et al., 2002; Piron et al., 2004, 2009). However, most such telerehabilitation programs require regular monitoring by or direct interaction with a rehabilitation specialist. Not all programs have the capability to quantify performance throughout the intervention period and thus rely on pre-and post-assessments performed in a clinic or research setting. Such information has the potential to assist in modifying training as performance improves and to identify patterns of performance change. Understanding how change occurs over time may provide valuable insights into the nature of movement-dependent functional improvements which may be used to develop more effective individualized training programs. The nature of training using telerehabilitation is quite variable with some telerehabilitation programs utilizing a broad range of arm and hand activities (Holden et al., 2008; Huijgen et al., 2008), while others have focused on variants of a single task such as visually guided arm movements (Piron et al., 2009) or tracking tasks (Carey et al., 2007). Related to this is the fact that explicit training of movement-related somatosensory function is almost invariably excluded despite the importance, for example, of tactile feedback in hand manipulation tasks (Byl et al., 2002).

In an attempt to address these issues, we have developed a home and Internet-based sensorimotor training program aimed at improving arm and hand function in chronic disability conditions (Brown et al., 2010). Our Upper Limb Training and Assessment (ULTrA) program incorporates several reaching and hand manipulation tasks which are performed in a home setting with only periodic supervision by a rehabilitation specialist. The current system provides quantitative information regarding task performance throughout the training period. The program was initially designed for adults with cerebral palsy (CP) since chronic childhood onset disorders such as CP have poor access to traditional, hospital or clinical-based services once school years are completed and the transition to adulthood is made. Some of the results related to arm reaching, interlimb coordination and hand function, have been recently published (Brown et al., 2010). In this paper, we will describe new findings related to more complex tasks involving reaching, grasping and moving objects, patterns of change throughout the intervention period for different tasks, and the effects of training on upper limb position sense.

## 2. METHODS

### *2.1 ULTrA Training Program*

The ULTrA training system consists of a target reaching apparatus and several hand manipulation/discrimination modules. A laptop computer with user-friendly, interactive software is used to guide participants through a series of task-specific, sensorimotor training activities as well as warm up and cool down stretching exercises. For upper limb reaching tasks, movements are made to illuminated targets in the vertical or horizontal plane as specified by computer-controlled touch sensors embedded in an apparatus comprised of an upright and lower board (Fig. 1A). Unilateral, bilateral simultaneous, and bilateral sequential movements are performed depending upon the stage of training. Reach, grasp, and release tasks are also performed which require grasping and moving a cone-shaped object from one position to another on the horizontal aspect of the target apparatus and then returning the hand to a home target location. The ability to perceive and identify patterns using only tactile feedback is quantified using a custom-designed device into which the participant inserts his/her hand and scans different patterns of raised pins embedded along all four sides of a square plastic base (Fig 1B). Time-based, hand manipulation tasks include identification of computer-specified objects in the absence of vision (stereognosis), sliding or turning playing cards (Fig 1C), moving objects from one location to another using a pincer grip or modified chopsticks (Fig 1D), and manipulating metal chiming balls (Fig. 1E). Participants are required to identify the correct pattern from a series of possible patterns displayed on the computer in a preset amount of time. Sensor data related to reach duration, interlimb coordination and hand manipulation tasks are saved as text files to the laptop throughout each training session and then sent to the laboratory using either a TCP/IP protocol or a VPN connection. Webcams are used periodically throughout the training period to monitor and progress participants and to ensure that participants accurately record performance during the hand training tasks.

### *2.2 Upper Limb Training in Adults with Cerebral Palsy*

Twelve adults diagnosed with CP (4 males, 8 females, 20.7 to 57.2 years) and with primarily unilateral upper limb involvement were enrolled in an 8 week training program using the telerehabilitation system described above. Participants were considered mildly to moderately impaired according to the Gross Motor Function Classification System (GMFCS), a 5-level scale where Level V represents the greatest functional impairment (McCormick et al., 2007; Palisano et al., 1997). Self-reports of the amount of upper limb use and the perceived quality of motion using the Motor Activity Log (Uswatte et al., 2006) indicated significant impairment according to a six point scale where 0 indicates the arm is never used and 5 indicates performance of the more affected arm is the same as the less affected arm. Training occurred for approximately 45 min a day, five days a week. Of the 12 participants, 10 ambulated independently, one used a walker and one used a motorized chair. All participants lived independently in the community and none were receiving therapy or medication related to upper limb function at the time of the study. All gave informed consent according to protocols established by the University of Michigan Institutional Review Board.

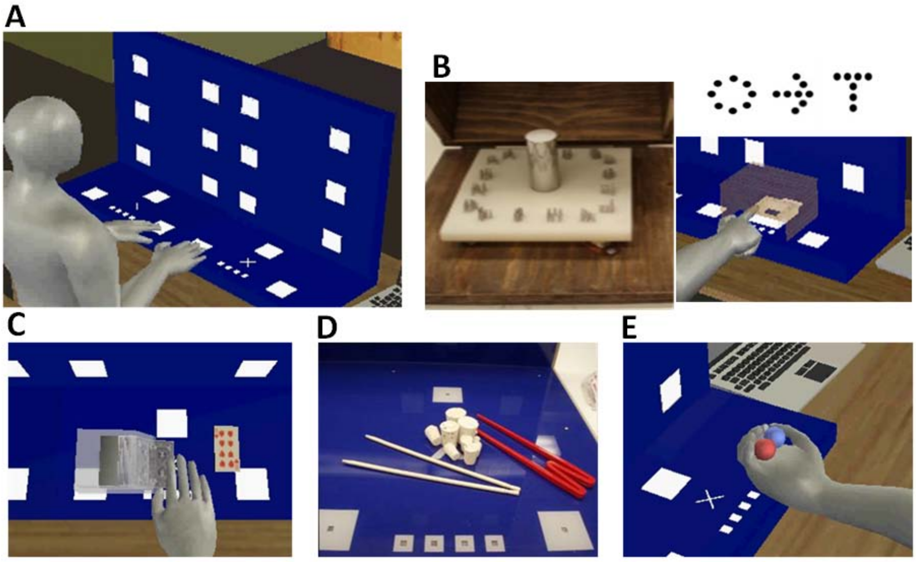


**Figure 1.** *Components of the ULTrA telerehabilitation program include an instrumented target reaching board (A), a tactile discrimination unit comprised of patterns of raised pins embedded in a plastic base (B), and several object manipulation tasks including card sliding/turning (C), moving objects with modified chopsticks(D), and rolling metal balls back and forth the palm of the hand (E).*

**Table 1**. *Participant characteristics (age, affected side, and functional assessment scores at baseline).*

| Participant | Age yr | More Affected | Motor Activity Log Amount of Use | Motor Activity Log Quality of Motion | GMFCS |
|---|---|---|---|---|---|
| 1 | 40.8 | left | 2.62 | 3.38 | II |
| 2 | 24.7 | right | 2.99 | 3.58 | I |
| 3 | 36.8 | right | 0.75 | 0.75 | I |
| 4 | 35.1 | right | 1.11 | 0.82 | I |
| 5 | 34.2 | left | 0.96 | 1.05 | I |
| 6 | 38.0 | left | 0.68 | 0.68 | II |
| 7 | 21.9 | right | 0.86 | 0.64 | I |
| 8 | 22.8 | right | 1.71 | 1.93 | I |
| 9 | 20.7 | left | 1.25 | 1.21 | I |
| 10 | 57.2 | right | 1.64 | 1.61 | III |
| 11 | 41.5 | right | 1.79 | 1.57 | IV |
| 12 | 32.5 | right | 0.5 | 0.39 | I |

Pre- and post-intervention clinical assessments included the Motor Activity Log, the Nine-Hole Peg Test, grip strength, and tactile spatial discrimination using JVP domes (Bleyenheuft and Thonnard, 2007). Upper limb proprioception using a position matching paradigm established by our laboratory (Goble and Brown, 2007, 2008; Goble et al., 2009) was also measured prior to and immediately following the intervention. Compliance was high with all participants completing 40 training sessions. Less than one percent of data were lost due to difficulties with data recording or transmission.

### 2.3 *Data Acquisition and Analysis*

Computer-determined reach locations were presented as illuminated square targets containing proximity sensors. When touched, the sensors generated timing information which was stored on the computer. For the hand manipulation and tactile discrimination tasks, participants used interactive software in order to record performance (e.g. number of cards turned). After each training session, data were transferred to the laboratory via the Internet. The effects of training on each dependent variable were determined using the nonparametric Wilcoxon signed rank test for paired comparisons.

## 3. RESULTS

### *3.1 Arm Reaching Performance*

As previously reported, the ULTrA telerehabilitation program led to improved reaching performance in adults with CP. This was seen as a significant reduction in the time to perform reaching movements using the more affected arm during unilateral, bilateral simultaneous, and sequential movements (Brown et al., 2010). In more complex reach and grasp tasks, mean movement time across all participants decreased for both the transport (time to grasp and move an object) and release (time to release object and return to home position) components of the task. This is shown for the more affected hand in Fig. 2 during unilateral reaching. Based on data obtained from each training session, a novel feature of our training system, changes in performance were found to be variable both within and across participants for the reach/grasp task. Examples of performance change during the transport component are shown for three participants in Fig. 3. While movement time associated with object transport decreased for participants A and B by the end of the training, improvement occurred more quickly and with less session to session variability in participant A compared to participant B. The only participant to not show an improvement in this task (C) improved over the first three weeks, after which performance worsened and was quite variable.

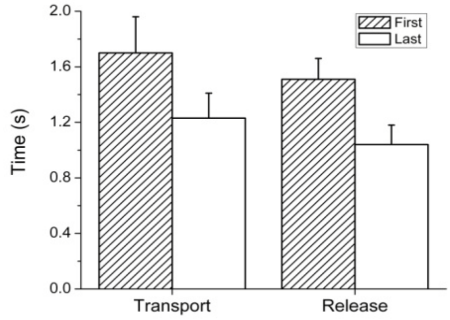


**Figure 2.** *Mean time required to reach, grasp and place an object (transport) and release and return to home position (release) during the first and last training session (more affected hand). Data are mean ( +1 SE) for all 12 participants (p<.01).*

### *3.2 Object Manipulation*

Several of the training tasks focused on manipulation of objects in the absence of vision (stereognosis), or using tools such as modified chopsticks. In the card sliding/turning task, all participants showed improvement over the course of training. This is illustrated in Fig. 4A for one participant performing card sliding (weeks 1-3) followed by card turning (weeks 4-8). The latter task was considered more challenging since forearm supination, frequently impaired in CP, was required to complete the task. When participants progressed from card sliding to turning, a marked reduction in the performance of both hands was often seen. This is illustrated in Fig 4A where a gradual improvement in performance of the more affected hand was seen over the remaining five weeks. The magnitude of change in the card turning task varied across participants as shown in Fig. 4B. In one of the 12 participants, performance declined after the training period and in another there was no change between the first and last training sessions. In the other 10 participants, the ability to grasp and turn cards improved by 10 to 250 percent.


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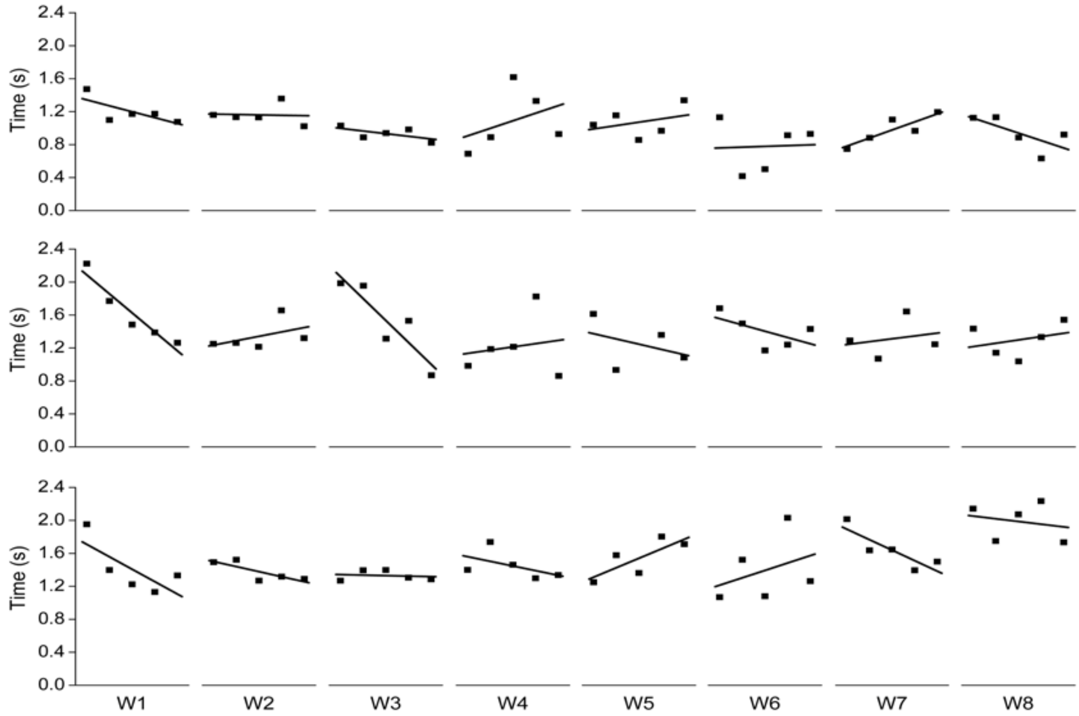


**Figure 3**. *Patterns of change in transport time for three participants (A-C). Each data point is the average from a single training session. Linear regression lines have been plotted for weekly data (W1-W8).*

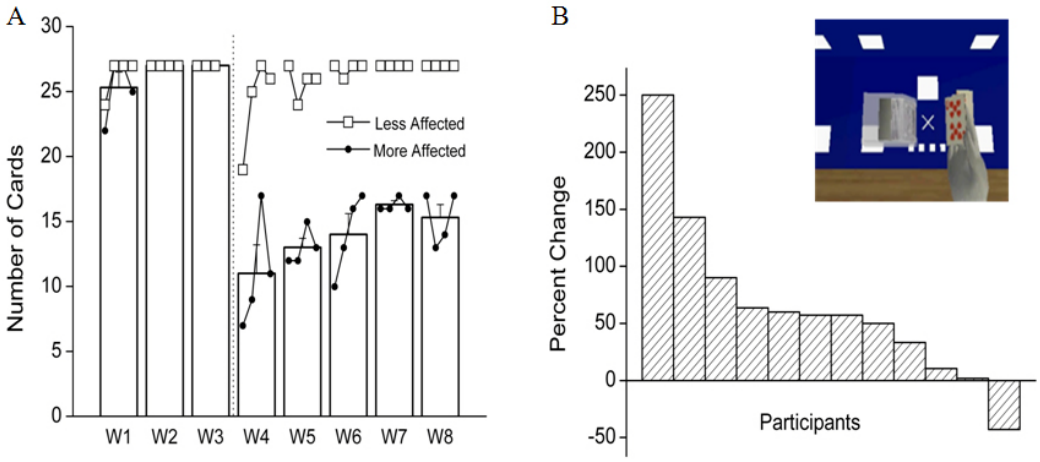


**Figure 4.** *The graph A shows the number of cards slid from the card holder during the first three weeks (W1-3) and turned during the remainder of the training period (W4-8) for one participant (open symbols – less affected hand, filled symbols – more affected hand). Each data point represents one training session. Bars represent average (+ 1 SE) weekly performance. Dashed line represents time when participant was progressed from card sliding to card turning. The graph B shows the percent change in card turning (image inset) for each participant ranked on the basis of the magnitude of improvement.*

*3.3 Movement-related Somatosensory Function*

In addition to improved motor ability with training, there was also improvement in movement-related somatosensory function as evidenced by an enhanced ability to use tactile feedback in a pattern discrimination task and a reduction in errors associated with position matching tasks. In the tactile discrimination task at the beginning of training, mean accuracy in correctly identifying pin patterns with the more affected hand was 60 compared to 83 percent when using the less affected hand. However, mean accuracy significantly improved over the course of training to 71 percent (Brown et al., 2010). Slight gains were also noticed in the performance of the less affected hand with training but differences were not statistically significant. Examples of individual patterns of improvement in tactile discrimination over the course of training are shown in Fig. 5. While most participants made steady gains during the first week of training (W1), subsequent weekly performance was variable in most participants. In the examples shown, this is most notable in weeks 3-5. Despite week to week variability, however, all participants continued to improve in their ability to correctly identify pin patterns based only on tactile feedback.

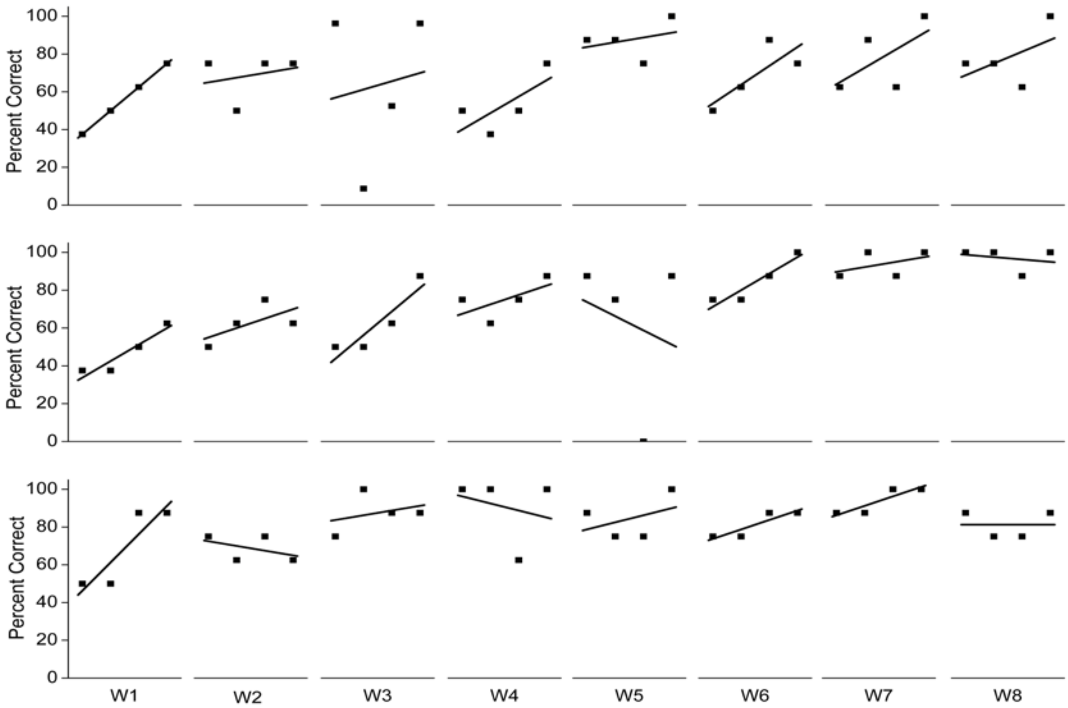


**Figure 5.** *Patterns of change in transport time for three participants (A-C). Each data point is the average from a single training session. Linear regression lines have been plotted for weekly data (W1-8). Data shown in A and B are from the same participants shown in Figure 3A and B.*

In addition to improvement in tactile discrimination with training, the ability to accurately reproduce elbow position improved in several but not all participants. In tasks where participants were required to actively match a passively determined elbow reference position with the same arm, errors were reduced in six of the 12 participants regardless of which arm was performing the matching task (Fig. 6). It should be noted that errors produced by the less affected arm prior to training were, for most participants, greater than those seen in non-disabled, age-matched individuals performing the equivalent task (approximately 3 deg, Goble and Brown 2008). The observation that matching errors decreased with training for some participants suggests that, even though position sense was not directly targeted as part of the training program, repetitive practice of goal-directed motor tasks may carry over to movement-related proprioceptive ability.

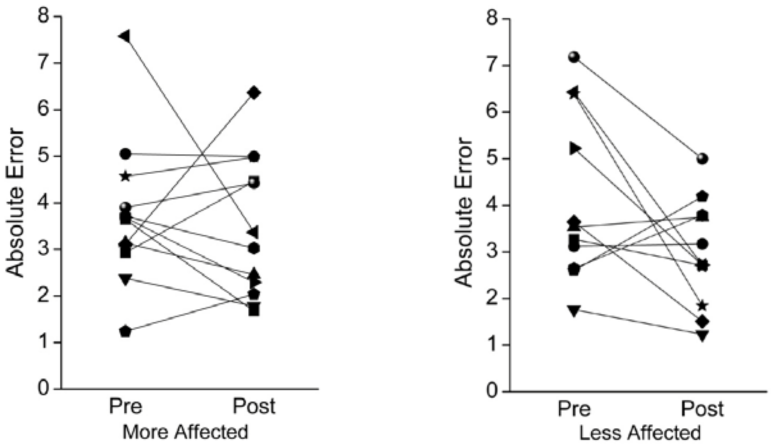


**Figure 6.** *Elbow position matching errors (deg) for the more affected and less affected arms. Each data symbol represents an individual participant.*

*3.4 Functional Changes*

Scores on both components of the Motor Activity Log improved following the intervention although gains were relatively modest (Brown et al., 2010). Evaluation of performance on the Nine-Hole Peg test, a measure of hand dexterity, was based on 10 participants in whom a mean improvement of 14.6 percent was observed during the post-intervention assessment. Grip strength of the affected but not the less affected hand also increased.

Participant feedback regarding the ULTrA program was positive even though experience using computers was quite variable. Indeed, our oldest participant who had never used a computer, purchased her own at the end of the program. Flexibility regarding when training occurred was viewed as a major factor contributing to the high degree of compliance observed in the study. Examples of comments from individual participants following completion of the ULTrA program include the following:

> "I became aware the arm is there and able to do (things)."
>
> "I was really surprised. I honestly didn't expect to see such a difference…I didn't gain more strength, but I gained control of my left hand."
>
> "I didn't even realize how my right side was deteriorating because I wasn't using it."
>
> "I can use both hands when I am dressing and driving the car… I always used my left arm to reach across and turn on the ignition key…. I don't do that anymore."

## 4. DISCUSSION AND FUTURE DIRECTIONS

These results demonstrate the effectiveness of a telerehabilitation system to improve upper limb function in adults with CP based on performance data obtained from various training tasks. Despite the chronic nature of the motor impairments, relatively short training sessions of less than an hour a day led to significant improvement in reaching and object manipulation ability as well as improved tactile discrimination. Only intermittent monitoring by a rehabilitation specialist was required during the training period which allowed participants to choose training times which were most convenient for them. The use of a computer-based system was not viewed as a barrier to compliance and many participants were eager to pursue similar training activities once the intervention was completed.

The ability to generate and transmit quantitative measures throughout the intervention period is a distinct advantage over most rehabilitation approaches which rely on pre- and post-assessments to evaluate change. Quantifying daily performance of adults with chronic upper limb deficits using sensorimotor tasks paves the way for many new avenues of research with the potential to further the field of rehabilitation for all individuals with upper limb deficits. Tracking a simple metric such as number of task repetitions may help us understand appropriate dosage for upper limb rehabilitation. A more complex use of the module data from individual training sessions is the examination of learning patterns in order to create algorithms that may suggest appropriate progression of the participant. As this technology advances, we believe that telerehabilitation has an imminent role in providing optimal healthcare.

Current research is now focused on adapting the system for use in chronic stroke including the development of grasp and pinch force devices with real-time visual feedback aimed at improving fine force control in both unilateral and bilateral hand force tasks. Automated versions of the tactile discrimination and card turning tasks are also in development. Long term goals will be to create easily portable, stand alone modules so that clinicians can tailor intervention programs to the specific needs of their clients. This technology would encourage a more proactive approach to maximizing function throughout a lifetime in chronic conditions by making rehabilitation more accessible and less resource intensive than other therapeutic interventions. The training system does not need to be limited to chronic stages of rehabilitation. It would also have applicability to acute and subacute stages where repetitive task training has demonstrated improvements in mobility (Kwakkel et al., 1999). This reinforces the idea that intermittent telerehabilitation interventions may be used to promote maximum function throughout a lifespan.

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