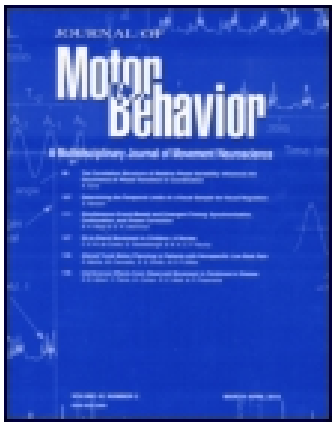

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# A Fully Automated, Quantitative Test of Upper Limb Function

Arthur Prochazka[a] & Jan Kowalczewski[a]
[a] Neuroscience and Mental Health Institute (NMHI), School of Molecular & Systems Medicine, University of Alberta, Edmonton, Canada
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*RESEARCH ARTICLE*

# A Fully Automated, Quantitative Test of Upper Limb Function

**Arthur Prochazka, Jan Kowalczewski**
Neuroscience and Mental Health Institute (NMHI), School of Molecular & Systems Medicine, University of Alberta, Edmonton, Canada.

**ABSTRACT**. The Rehabilitation Joystick for Computerized Exercise (ReJoyce, Rehabtronics Inc., Edmonton, Alberta, Canada), is a workstation on which participants exercise dexterous movement tasks in the guise of computer games. The system incorporates the ReJoyce Arm and Hand Function Test (RAHFT). Here the authors evaluate the RAHFT against the Action Research Arm Test (ARAT) and the Fugl-Meyer Assessment (FMA). All 3 tests were performed in 36 separate sessions in 13 tetraplegic individuals. Concurrent and criterion validities of the RAHFT were supported by a high level of correlation with the ARAT ($r^2 = .88$). Regarding responsiveness, the effect size of the RAHFT at week 6 of 1 hr/day exercise training was 1.8. Regarding reliability, the mean test–retest difference in RAHFT baseline scores was $0.67\% \pm 3.6\%$, which was not statistically significant. The RAHFT showed less ceiling effect than either ARAT or FMA. These data help validate the RAHFT as a quantitative, automated alternative to the ARAT and FMA. The RAHFT is the first comprehensive test of arm and dexterous hand function that does not depend on human judgment. It offers a standardized, quantitative outcome evaluation, which can be performed not only in the clinic, but also in the participant's home, administered by a remote therapist over the Internet.

*Keywords*: rehabilitation, upper extremity, hand



Upper limb (UL) motor deficits are major contributors to chronic physical disability following stroke and spinal cord injury. In North America more than 3 million people live with unilateral UL weakness or paralysis resulting from stroke or trauma (Rosamond et al., 2008). An additional 300,000 people with spinal cord injury (SCI) have bilateral UL weakness or paralysis. Up to 60% of all these people find it hard or impossible to perform activities of daily life (ADL; van der Lee et al., 1999).

There is evidence that intensive, structured exercise therapy (ET) can improve UL function (Van Peppen et al., 2004); however, adherence to conventional exercise protocols tends to fall off over time, particularly when clients leave rehabilitation facilities (Savage et al., 2001). Various approaches and devices have been developed over the last few years to address this problem. These include Constraint-Induced Movement Therapy (CIMT; Taub et al., 2006), computerized passive exercise devices such as the Nintendo Wii (Nintendo Co., Ltd., Kyoto, Japan), robotic devices (Volpe et al., 2009), therapeutic (TES) and functional electrical stimulation (FES; Peckham & Knutson, 2005; Stein & Prochazka, 2009), and in-home teletherapy (IHT; Gritsenko, Chhibber, & Prochazka, 2001; Kowalczewski, Gritsenko, Ashworth, Ellaway, & Prochazka, 2007; Krebs, Hogan, Aisen, & Volpe, 1998; Reinkensmeyer, Pang, Nessler, & Painter, 2002).

UL function tests are useful in tracking clients' progress and in directing their rehabilitation. Numerous clinical UL function tests have been developed and validated for clinical evaluation (Lang, Bland, Bailey, Schaefer, & Birkenmeier, 2013), but they all have qualitative components and are therefore prone to rater bias. Ideally, UL function tests should be performed on standardized equipment that allows various parameters of performance to be quantified. However, in order for this to be feasible, either in the clinic or in clients' homes, the equipment must be affordable, and the time taken to perform the assessments must be reasonable (e.g., less than 10 min). Kinetic and kinematic analysis systems have been developed for quantitative functional evaluation over the last few years. For example, UL motor ability tests have recently been incorporated in two robotic devices designed for UL exercise training, one validated for stroke (Krebs et al., 2014) and the other for spinal cord injury (Zariffa et al., 2012). The KinArm UL robot (BKIN Technologies, Kingston, Ontario, Canada) has also been assessed for quantifying range of motion (ROM) and kinesthesia in stroke and traumatic brain injury (Coderre et al., 2010; Debert, Herter, Scott, & Dukelow, 2012). Motion capture devices such as the Kinect (Microsoft Corp., Seattle, WA) have been adapted to quantify ROM (Kurillo, Han, Nicorici, & Bajcsy, 2014; Kurillo et al., 2013).

For an automated UL function test to become clinically accepted, first and foremost, it must be shown to be substantially equivalent to existing clinical tests. The equipment involved should incorporate software that automates the administration of the test and provides quantitative ratings of individual tasks as well as an overall score. Ideally the equipment should also be affordable by clinics and useable by clients for UL exercises. The Rehabilitation Joystick for Computer Exercise (ReJoyce, Rehabtronics Inc., Edmonton, Alberta, Canada) was developed by our group with these criteria in mind.

The ReJoyce is a passive workstation comprising a segmented arm that presents the user with a variety of spring-loaded attachments (Figure 1). Each attachment is instrumented with one or more sensors, whose signals are fed to a computer, which uses them to provide task-oriented, intensive arm and hand exercises in the form of computer games (Kowalczewski, Chong, Galea, & Prochazka, 2011; Kowalczewski & Prochazka, 2011b; Lange et al., 2010). An important feature of the device is the ReJoyce Arm and Hand Function Test (RAHFT). This is an

*Correspondence address: Arthur Prochazka, Neuroscience and Mental Health Institute (NMHI), School of Molecular & Systems Medicine, 507 HMRC, University of Alberta, Edmonton AB, Canada T6G 2S2. e-mail: arthur.prochazka@ualberta.ca*

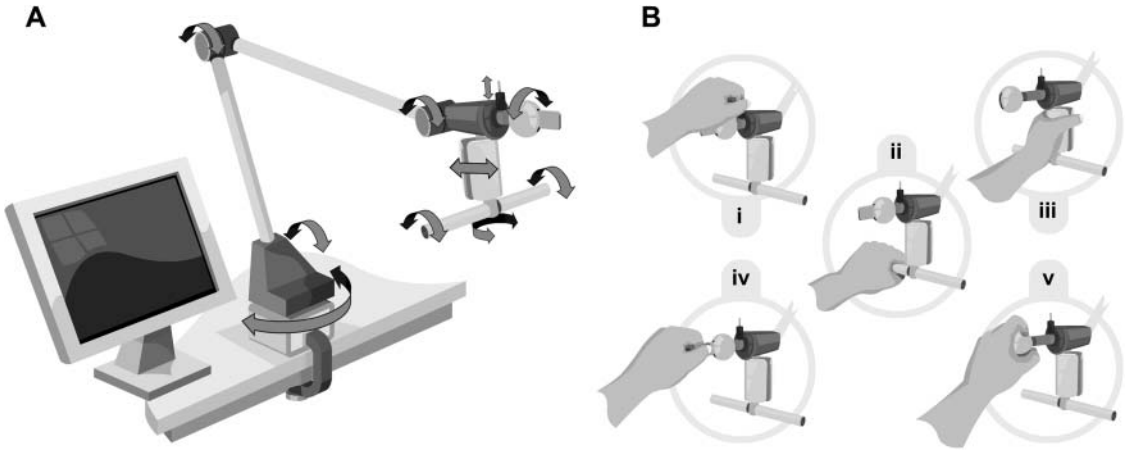


**FIGURE 1.** (**A**) Schematic of the Rehabilitation Joystick for Computer Exercise (ReJoyce). Subjects performed a variety of tasks while playing computer games, or performing the ReJoyce Automated Hand Function Test (RAHFT). The device is instrumented with sensors that provide quantitative information on displacement of the manipulanda, and the force of a grasp. (**B**) Types of grasp required to perform the RAHFT.



automated test, comprising a variety of motor tasks whose performance is quantified. Here we report on the psychometric properties of the RAHFT.

## Method

### *Participants*

The data in the present study were drawn from a randomized controlled trial (RCT) involving 13 people between the ages of 24 and 56 years old with tetraplegia resulting from a C5-C6 SCI. Two treatments were compared: six weeks of FES-assisted, telesupervised in-home exercise sessions on the ReJoyce workstation (treatment 1) and six weeks of telesupervised in-home conventional exercises (treatment 2). The RCT had a crossover design, whereby the two treatments were administered sequentially, in randomized order and separated by a one-month rest period. After completing the trial, five participants opted to repeat the study with their other arm, for which they were again randomized in terms of the order of treatment. This yielded a total of 18 ULs whose responses were analyzed. Clinical and demographic details of the participants, along with a full report on results and conclusions of the RCT have been published previously (Kowalczewski, 2009; Kowalczewski et al., 2011). Approval of the project was granted by the Health Research Ethics Board of the University of Alberta. All subjects provided written, informed consent. The study was registered with the National Institutes of Health (clinicaltrials.gov identifier NCT00656149).

### *Procedures*

As part of the outcome evaluation of the RCT, three UL tests were performed in randomized order in single sessions that took place at baseline (two sessions 2–7 days apart) and then at two-weekly intervals during the six-week treatment periods. The three tests were (a) the UL portion of the Fugl-Meyer Assessment (FMA; Fugl-Meyer, Jaasko, Leyman, Olsson, & Steglind, 1975; Gladstone, Danells, & Black, 2002), (b) the Action Research Arm Test (ARAT; Carroll, 1965; Lyle, 1981; Yozbatiran, Der-Yeghiaian, & Cramer, 2008), and (c) the RAHFT. The FMA and ARAT tests were videotaped and scored by a blinded, independent rater.

### *Apparatus*

Each of the six attachments in the ReJoyce workstation was designed to represent a task commonly encountered in daily life. A clamp at the base of the spring-loaded arm was used to attach the device to a table or desk. The arm had 4 degrees of freedom of movement and was instrumented with rotational potentiometers about each joint. In addition, there were switches, rotational potentiometers, and linear potentiometers in the attachments. The spring loading of the arm provided some elastic resistance to movement and ensured that the attachments returned to a neutral position when they were released. It also supplied some weight support to the user's hand and arm. The attachments included a pair of horizontal handles that could be rotated about their long axis, a vertical peg that could be lifted, a gripper the size of a pop can that could be squeezed, and a spring-loaded doorknob with an exposable key-like element, both of which could be independently rotated. The handles were situated at the bottom of the attachment assembly and in the neutral position of the arm they were at the level of the base of the device. The easiest task to perform was to grasp one or both of the horizontal handles and to pull the

attachment assembly in and out, up and down or left and right (Figures 1 and 2). The gripper, the doorknob, key, and peg were located above the handles in an approximately ascending order of difficulty of use.

We refer to an individual's UL workspace as the functional range of motion (fROM). This is the volume of space in which the person is able to grasp an object and perform a functional task with it. Similar to the ARAT, the ReJoyce system focuses not on the kinematics or kinetics of arm movement, but rather on a person's ability to move and manipulate objects within their fROM (i.e., it assesses function rather than impairment). It allows for a number of different grasps to be used as well as combinations of grasps and displacements that mimic tasks of daily life such as grasping and twisting a doorknob and opening a door. Figures 1 and 2 illustrate the attachments and some of the grasps and movements used during exercise sessions and the RAHFT. Participants were seated in a wheelchair or armless chair in front of the ReJoyce such that the plane of the more affected arm and forearm was approximately in line with the vertical plane of the ReJoyce arm. The rest position of the bottom of the ReJoyce attachment assembly was about 15 cm above the participant's more affected leg, about halfway between knee and hip.

A MAKE Controller Kit (MakingThings LLC, Oakland, CA) in the base of the ReJoyce arm digitized the analog signals from sensors in each component of the attachment assembly. The controller kit sent the information in digital



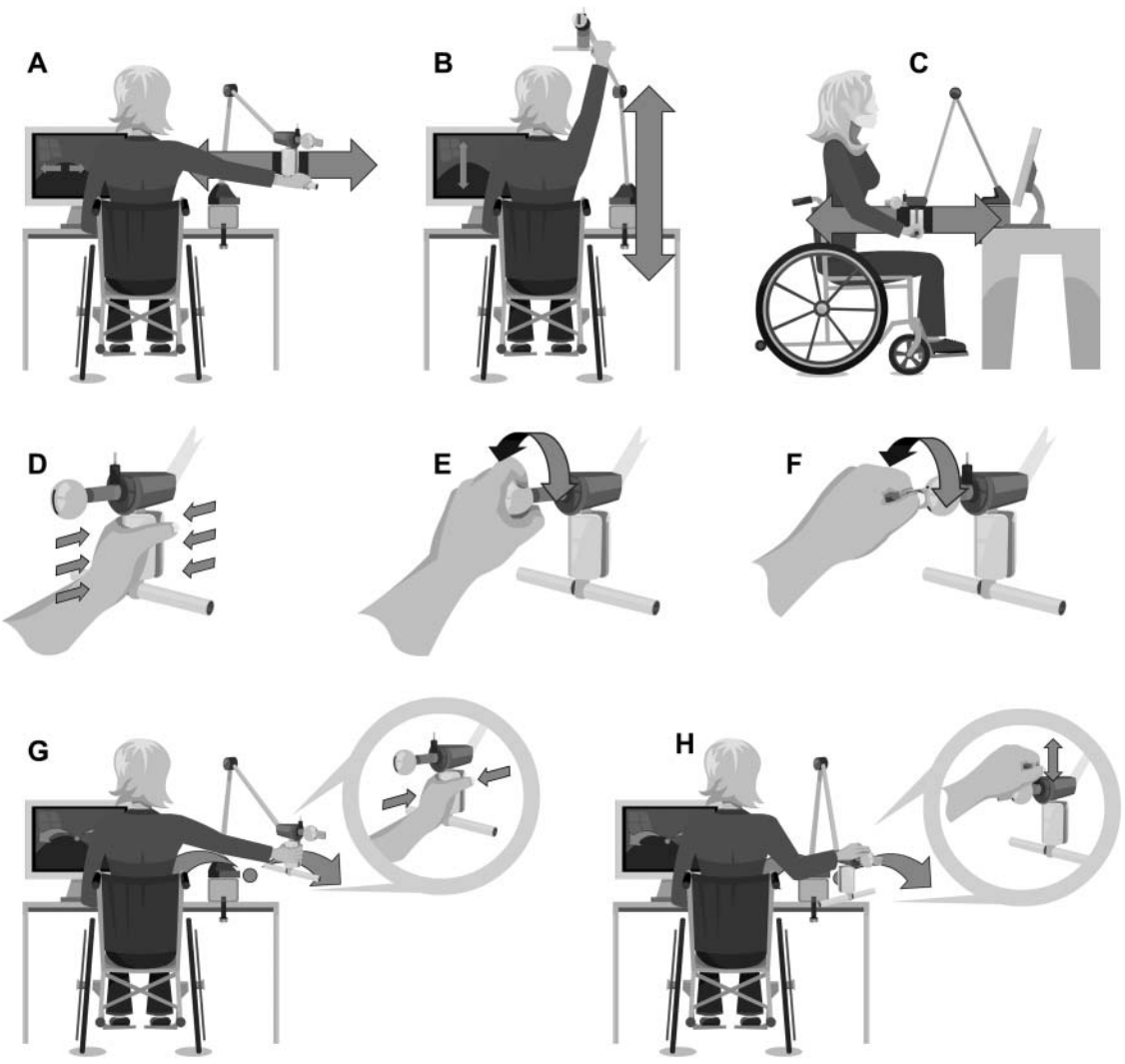


**FIGURE 2.** The Rehabilitation Joystick for Computer Exercise system, showing all components of the ReJoyce Automated Hand Function Test. (**A**) move to left and right; (**B**) move up and down; (**C**) move in and out; (**D**) grasp and squeeze rubber cylinder; (**E**) rotate spring-loaded doorknob; (**F**) rotate spring-loaded key; (**G**) grasp, move, and release, using the cylinder; (**H**) pinch peg, lift, move, and release.

form via a universal serial bus (USB) to a local computer. The information was processed by the computer with custom software that computed the coordinates of the arm segments and attachments in 3-dimensional space, the displacement of the gripper attachment, the rotation of the key or doorknob, and the elevation of the peg. These various signals were used by the software to control the RAHFT and interactive games.

*RAHFT*

The RAHFT consisted of three parts: (a) functional range of motion (fROM); (b) grasp, key-grip, and pronation–supination tasks; and (c) placement tasks (Figure 2). The users (subjects or therapists) initiated the RAHFT software program by clicking on a desktop icon, after which the program ran automatically, taking its cues from signals from the ReJoyce device or inputs from the subject's computer keyboard. As the test progressed, the RAHFT software introduced each component of the test with a three-dimensional animation accompanied by an audio recording, which ended with a 3-s countdown. The user was then allowed up to 60 s to perform the task. If the task was completed within this time, the user or therapist could advance to the next task by depressing the keyboard spacebar. On some occasions the RAHFT was also performed remotely during telesupervision sessions, but these data are not included in this report, as they were not obtained with concurrent FMA and ARAT tests.

1. fROM. The subject was first asked to hold the horizontal handle on the attachment assembly and move it as far to the left and then as far to the right as possible (Figure 2A). Sixty seconds were allocated for this task. The second and third tasks were similar, comprising up and down and in and out ranges of motion (Figure 2B and 2C). The spring-loading of the attachments provided a spring stiffness of 16 N/m, in the left and right direction ($x$-axis), 26 N/m in the up and down direction ($y$-axis), and 20 N/m in the in and out direction ($z$-axis).
2. Grasp. The subject was asked to grasp and squeeze the gripper on the attachment assembly three times as hard as possible. The gripper was a spring-loaded, split cylinder the size of a pop can. It required 10 N of force to be applied to bring the two halves of the cylinder together through a distance of 1.5 cm. The spring stiffness in this range of movement was 667 N/m.
3. Doorknob. The subject rotated a spherical, spring-loaded doorknob clockwise and counterclockwise, the mechanism being based on that of commercially available doorknobs with a rotational stiffness of 0.34 Nm/rad.
4. Key. The subject rotated a spring-loaded key-shaped object normally hidden within the doorknob attachment (same rotational stiffness as the doorknob). Pushing the doorknob inward along its shaft exposed the key and closed a switch, which informed the system of activation of the key task.
5. Placement tasks. The first of these involved picking up a virtual pop can displayed on the computer screen. The gripper was grasped loosely and moved so as to position crosshairs on the monitor to overlie an image of a pop can. The gripper was then squeezed to hold the virtual pop can and move it to a position over one of two virtual garbage bins located on each side of the screen. The pop can was then dropped into the bin by releasing the gripper. A new pop can then appear in the middle of the screen, requiring the subject to grasp, move, and drop it into the other bin. The second placement task was similar, in that it required a peg located at the top of the assembly to be grasped, lifted, moved, and released. A corresponding virtual peg was displayed on the subject's screen. The task was to move it over one of two virtual holes and release it. As in the case of the pop can task, a second virtual peg then appeared and this had to be dropped into the second virtual hole. In both placement tasks, if the object was not dropped into the appropriate receptacle, the task had to be repeated until it was completed successfully or the full 60 s allocated to the test had elapsed.

*Scoring the RAHFT*

All fROM tasks were scored as a percentage of the maximal displacement of the handle in the required direction (e.g., left, right, up, down). The grasp, doorknob, and key tasks were similarly scored as percentages of the maximal displacement possible (Table 1). Each placement task comprised two components: a movement to the left and a movement to the right. In this case each component was scored in

**TABLE 1. Spring Stiffnesses and Range of Motion of the ReJoyce Manipulanda Used in the RAHFT**

| RAHFT task | Stiffness | Range |
|---|---|---|
| fROM $x$-axis | 16 N/m | 1.6 m |
| fROM $y$-axis | 26 N/m | 1.2 m |
| fROM $z$-axis | 20 N/m | 1.04 m |
| Gripper (compression) | 670 N/m | 0.015 m |
| Doorknob (rotation) | 0.34 Nm/rad | 174° |
| Key (rotation) | 0.34 Nm/rad | 174° |
| Peg (vertical lift) | 25 N/m | 0.5 cm |

*Note.* ReJoyce = Rehabilitation Joystick for Computerized Exercise; RAHFT = ReJoyce Arm and Hand Function Test; fROM = functional range of motion.

terms of the time to completion according to the equation:

$$\text{score} = 50 - (\text{time(s)} * 5/6) \quad (1)$$

Thus, if a left placement (e.g., dropping a pop can into the left bin) was performed in say 6 s the score for that portion was 45. If the subsequent right placement was also completed in 6 s, it also scored 45 and so the summed score for that task was 90%. On the other hand, if the left placement took 6 s and the right placement took 30 s, the summed score was 70%. Note that the maximal time allocated for the test was 60 s. The coefficient 5/6 in the equation was selected such that at 60 s the score reaches zero.

At the end of the RAHFT the software automatically computed the overall RAHFT score as the mean of all the individual task scores.

### *Statistical Methods*

As each of the UL tests had different maximal scores (RAHFT 100, ARAT 57, FMA 66), for ease of comparison, we normalized the raw scores to percentages of the corresponding maxima. Data were analyzed with the use of Matlab version 7.0.1 (The MathWorks, Natick, MA) software. Simple linear regressions and calculations of test–retest differences, correlation coefficients, and principal components (PCs) were also performed with this program.

## Results

The three UL tests were performed in randomized order during single test sessions. Two test sessions spaced by a few days took place at baseline for each of the 18 ULs. In the 3D plot of Figure 3, the resultant 36 normalized RAHFT, ARAT, and FMA scores are represented by open circles. The first three PCs of the data set are shown as orthogonal lines running through the data points in Figure 3. PC1, which accounted for 91% of the variance in the data, is shown as the long bold line.

It is customary to validate a new motor test by comparing it to existing, validated tests. In this case we were interested in validating the RAHFT against the ARAT and FMA. Figures 4 and 5 show plots and linear regressions of the RAHFT scores against those of the ARAT and FMA. For the sake of comparison, we also included plots and regressions of the FMA and ARAT against each other. The RAHFT was well correlated with the ARAT ($r^2 = .88$), and in fact much better correlated than was the FMA with the ARAT ($r^2 = .53$). Not surprisingly, in view of these results, the RAHFT and ARAT were only moderately correlated with the FMA ($r^2 = .49$ and .53, respectively). Given that the FMA mainly tests ROM, we performed a subanalysis in which we only included the fROM scores in the RAHFT. This increased the coefficient of determination $r^2$ of RAHFT with respect to FMA from .49 to .60.

Figure 6 shows mean changes in normalized RAHFT and ARAT scores in the 9 participants who performed six weeks of FES + ReJoyce training prior to crossover (Kowalczewski, 2009). To quantify responsiveness, we calculated the effect sizes in Figure 6 (change in mean scores from baseline to week 6 divided by the standard deviation of the baseline score; Lang, Wagner, Dromerick, & Edwards, 2006). Table 2 shows that the time courses of RAHFT and ARAT effect sizes were comparable, both exceeding 1 at week 6 of treatment. The ARAT effect size at week 6 (1.2) was somewhat higher than the effect sizes reported in a recent study of a large group of tetraplegic individuals ranging from C3 to T1 injury level, after three months of conventional rehabilitation (Van Lieshout Test: 0.71–0.81; Grasp Release Test: 0.75–0.82; Spooren et al., 2006).

To quantify test–retest reliability, we analyzed the RAHFT, ARAT, and FMA scores obtained in the pairs of baseline evaluations performed before the onset of the first treatment and also those performed before the onset of the second treatment (after crossover). In each pair, the evaluations were separated by between two and seven days. A total of 34 test–retest pairs were available. Table 2 shows the mean and standard deviation of the first test scores of each pair and the mean test–retest difference (0.67% $\pm$ 3.6%). A Student's $t$ test of paired test–retest RAHFT scores indicated that there was no significant difference ($p = .31$, $n = 34$).

Regarding the duration of the tests, the ARAT took the longest time to administer with a mean time of completion of 7.8 $\pm$ 1.6 min, followed by the FMA, which took a mean time of 5.2 $\pm$ 1.0 min, and the RAHFT, at 3.8 $\pm$ 0.9 min.

## Discussion

The purpose of this study was to see how well the RAHFT correlated with two widely accepted and validated clinical UL tests, the ARAT and the FMA. Simple regression analysis was used to quantify the relationships between the three tests (Lang & Beebe, 2007). The correlation between the RAHFT and ARAT was stronger than that between the FMA and the ARAT. In retrospect, the greater correlation between the RAHFT and ARAT was to be expected, as these tests are designed to assess UL function in ADLs, whereas the FMA primarily focuses on range of motion at individual joints (i.e., it provides a measure of motor ability rather than function).

Figure 3 shows that at the top end of the range, subjects scored nearly 100% of full scale on the ARAT and FMA whereas the corresponding RAHFT scores were less than 70% of full scale, which is in line with previous reports indicating that the ARAT and FMA exhibit ceiling effects (Gladstone et al., 2002; van der Lee, Roorda, Beckerman, Lankhorst, & Bouter, 2002). This was also supported by our anecdotal observation that some of the SCI subjects we tested who received nearly perfect ARAT scores had clear

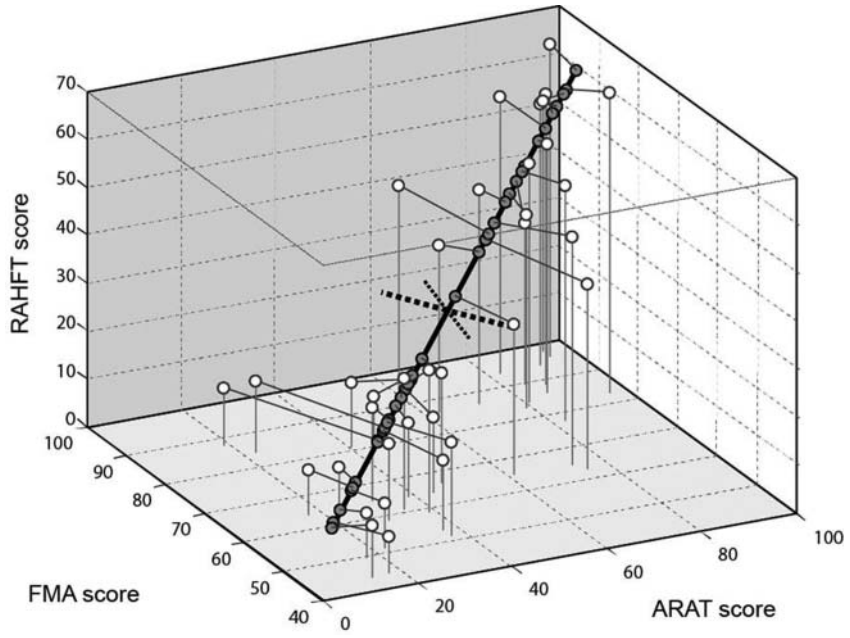


**FIGURE 3.** Three-dimensional plot of Action Research Arm Test (ARAT), Fugl-Meyer Assessment (FMA), and ReJoyce Automated Hand Function Test (RAHFT) scores from 34 test sessions. Each open circle shows the normalized scores of the three tests in a given participant in a given test session. The solid line is the first principal component (PC1) of the data points, and the dashed lines are PC2 and PC3. The grey circles are the nearest points on PC1 to each data point.

deficiencies in UL function compared to normal individuals. In other words, the RAHFT is able to track changes in UL function in high-functioning subjects beyond the upper limits of the ARAT and FMA. This is crucial in light of a recent study in stroke participants who reported using their more affected UL significantly in ADLs only if their ARAT score was 54 (95%) or higher (Fleming, Newham, Roberts-Lewis, & Sorinola, 2014). At the other end of the scale,

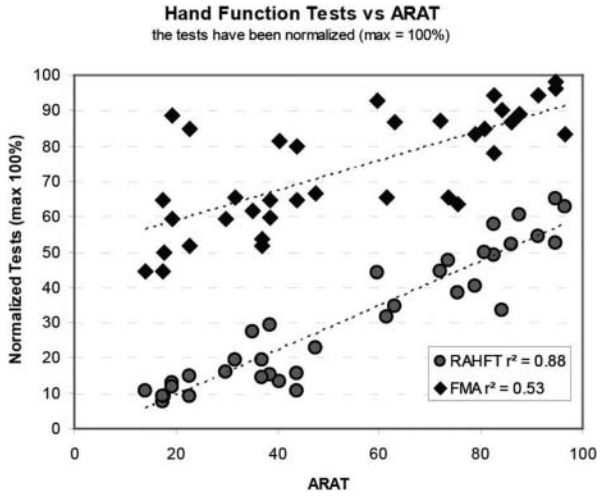


**FIGURE 4.** Individual plots of the ReJoyce Automated Hand Function Test (RAHFT) and the Fugl-Meyer Assessment (FMA) versus the Action Research Arm Test (ARAT), with regression lines and $r^2$ coefficients. The RAHFT correlated significantly better with the ARAT than did the FMA.

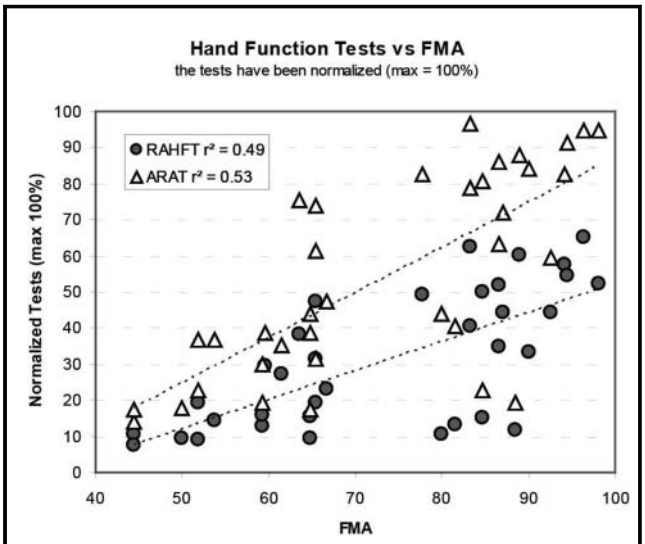


**FIGURE 5.** Individual plots of the ReJoyce Automated Hand Function Test (RAHFT) and Action Research Arm Test (ARAT) versus the Fugl-Meyer Assessment (FMA), with regression lines and $r^2$ coefficients.

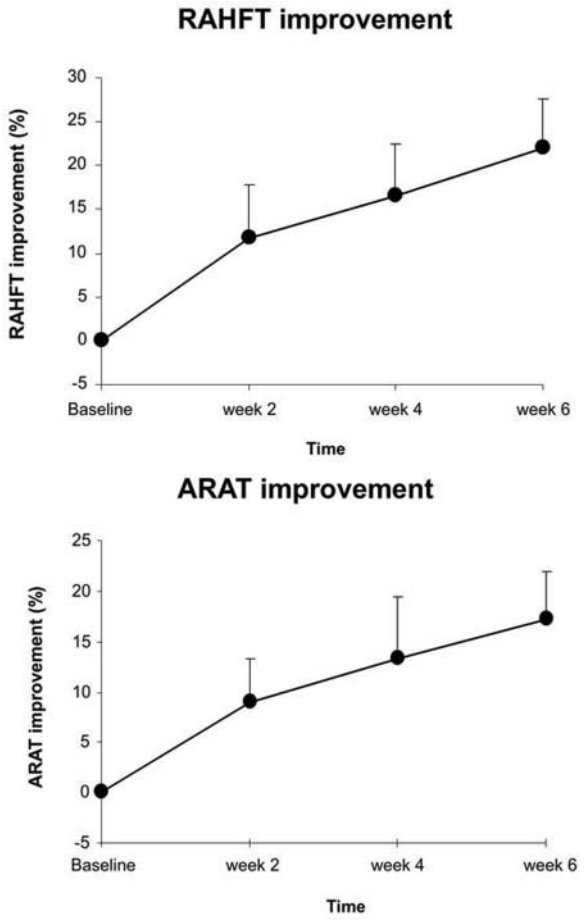


**FIGURE 6.** Mean changes in normalized ReJoyce Automated Hand Function Test (RAHFT) and Action Research Arm Test (ARAT) scores in the nine participants who performed six weeks of functional electrical stimulation (FES) + ReJoyce training prior to crossover. At weeks 2, 4, and 6, the RAHFT and ARAT were tested immediately before and after a 1-hr FES + ReJoyce training session. These results provide evidence of test–retest reliability and responsiveness of both tests (test–retest differences and effect sizes at weeks 2, 4, and 6 are shown in Table 2). This is part of Figure 3, Chapter 5, in Kowalczewski's (2009) doctoral thesis.

there was a potential floor effect in the ARAT and RAHFT, in that low-functioning subjects who had little active grasp or release, but who nonetheless had a reasonably good ROM, received near-zero scores. The corresponding FMA scores were above 40% of full scale, indicating that the FMA may have an advantage in this respect. It is sensitive to small movements that are not necessarily functional. The FMA might therefore be more useful than the ARAT and RAHFT in detecting small changes in the range of motion of the UL following an intervention in low-functioning subjects.

Regarding the applicability of our findings to other motor disorders, the majority of the SCI participants in our study had a good to very good ROM about the shoulder and elbow, resulting in relatively high FMA scores. In people with hemiparesis caused by stroke or head trauma, poor hand function is generally coupled with poor mobility about the proximal joints. Further testing is underway to determine the relationship between the RAHFT, ARAT, and FMA in hemiparesis and other motor disorders.

When assessing new tests of motor function it is common to evaluate interrater reliability, validity, and responsiveness. The concurrent and criterion validities of the RAHFT are supported in our study by the high level of correlation with the ARAT, which has been shown to have construct validity for ADLs (Carroll, 1965). Regarding responsiveness, the effect size of the RAHFT at week 6 in the data shown in Figure 6 was 1.8. Effect sizes greater than 0.8 are generally considered to be large (Lang et al., 2006; Spooren et al., 2006). Regarding reliability, the RAHFT is not subject to the variance in conventional clinical testing resulting from differences in procedure and scoring by human raters. However, other factors could have caused random variance, for example sensor noise. The data in Table 2 indicate that the test–retest differences were small and not statistically significant. Another concern would be systematic differences between different devices. Commercial versions of the ReJoyce, now deployed in over 250 facilities, are made and tested to exacting regulatory standards, with $<1\%$ tolerances in the measured variables shown in Table 1. However other sources of variance that are common to most, if not all, existing motor function tests are likely to remain. For example although our protocol includes guidelines for positioning the subject in relation to the device, as do some of the existing clinical tests, there is a limit to how well this can be defined and adhered to.

Some researchers advocate restraining the upper body with straps to minimize compensatory movements of the trunk (Michaelsen, Dannenbaum, & Levin, 2006; Michaelsen, Luta, Roby-Brami, & Levin, 2001). Although this has merit, it is not generally implemented clinically during training, nor has it been done in most research studies. Indeed in a proposed standardized set of procedures for performing the ARAT, trunk restraint was advised against. Instead, participants were to be encouraged to maintain trunk contact with the backs of their chairs (Yozbatiran et al., 2008). For consistency, we therefore chose not to use trunk restraint in our study.

We did not take into account differences in anatomy and muscle properties between participants that would physically limit the maximal possible ROM, hand aperture and, grasp force. One or more scaling factors related to measures such as shoulder to fingertip length could in principle be used to normalize the scores between participants. Likewise, it may be desirable to account for age- and

**TABLE 2. Mean Test–Retest Differences and Effect Sizes of the Tests Shown in Figure 6 at Weeks 2, 4, and 6**

| Test | Effect sizes of FES+ReJoyce treatment (pre–post difference/baseline *SD*) | | | Baseline test scores (%) | Baseline test–retest difference (%) |
|---|---|---|---|---|---|
| | Week 2 | Week 4 | Week 6 | | |
| RAHFT | 0.97 | 1.4 | 1.8 | 30.3 ± 18.5 | 0.64 ± 3.6 |
| ARAT | 0.57 | 0.94 | 1.2 | 53.5 ± 27.4 | 1.3 ± 6.3 |
| FMA | 0.32 | 0.51 | 0.73 | 72.9 ± 16.0 | 1.5 ± 5.2 |

*Note.* FES = functional electrical stimulation; ReJoyce = Rehabilitation Joystick for Computerized Exercise; RAHFT = ReJoyce Arm and Hand Function Test; ARAT = Action Research Arm Test; FMA = Fugl-Meyer Assessment.



gender-related differences in maximal grasp force in the gripper measurements. This would clearly need a separate, detailed validation study on a sizeable cohort of able-bodied individuals, which is beyond the scope of the present work. Note that most clinical tests of upper limb function such as the ARAT use objects (e.g., blocks, cylinders, weights) of a single specified size and reaching tasks involving specific path lengths. The clinical tests do not take into account anthropomorphic differences between participants.

Another factor that can lead to variance is the degree to which subjects comply with the automated audiovisual instructions. In the present study, a therapist was always present to ensure adherence to each portion of the RAHFT (as well as the ARAT and FMA). In theory a remote therapist conducting the RAHFT via the built-in teletherapy link could provide adequate oversight of adherence as well as positioning and compensatory movements of the trunk, but this remains to be confirmed. Likewise, the validity of self-evaluation by participants in the complete absence of supervision remains to be demonstrated. One safeguard we have since built into the ReJoyce software is the automatic detection of an absent response to an instruction, which triggers up to two repeats of the instruction before the system passes on to the next component of the test.

Regarding validity, the regression and principal components analysis showed that the RAHFT compared well with two widely accepted clinical tests, the ARAT and FMA. It would be desirable to expand this comparison to include other types of tests such as SCIM (Spinal Cord Independence Measure; Catz, Itzkovich, Agranov, Ring, & Tamir, 1997) and FIM (Functional Independence Measure; Hamilton, Laughlin, Fiedler, & Granger, 1994). The RAHFT correlated better with the ARAT ($r^2 = .88$) than with the FMA ($r^2 = .49$). This was not too surprising, because several components of both the RAHFT and the ARAT represent specific types of functional movement, whereas most tasks in the FMA are non-functional.

The primary purpose of the ReJoyce system is to serve as a workstation for rehabilitation of UL function. The RAHFT was developed when it was realized that the signals from the sensors enabled not only the control of computer games, but also the quantification of performance. The situation whereby the device is used both as a rehabilitation tool and as a means of assessment has the advantage that each user's progress can be accurately monitored on a regular basis, especially as the test can be performed in less than 5 min. However, the disadvantage of frequent testing is that there would most likely be a training effect, so that the results obtained on the RAHFT would not necessarily generalize to a larger variety of tasks encountered in daily life. It will be important to clarify this issue in the future, since the RAHFT can be performed in the subject's home on a daily basis with or without telesupervision, if so desired.

A disadvantage of machine-based quantification is that the machine must be available. As mentioned above, three robotic devices designed for UL exercise training now incorporate UL motor ability tests (Coderre et al., 2010; Krebs et al., 2014; Zariffa et al., 2012). All three of these devices cost well over $50,000. The ReJoyce is a passive device costing around $10,000. Though this still represents an obstacle to widespread deployment and use, the ReJoyce system has been adopted by over 250 clinics and research laboratories in 15 countries in the last 2 years. It is therefore available to a significant number of clinicians and researchers at the present time.

None of the robotic devices incorporate tasks such as those in the RAHFT involving dexterity of the fingers and hand (e.g., key grasp and rotation, peg grasp and lift, grasp release and placement of objects). This may explain the somewhat lower correlations with conventional clinical tests reported for the robotic devices compared to those in the present report. UL tests based on motion capture systems such as the Microsoft Kinect are the most affordable systems (costing between $1,000 and $2,000, including the computer); however, currently their measurements are limited to the ROM of shoulder and elbow in the absence of limb loading. Measurement of grasp force, pinch-grip force, and dexterous tasks with objects having mass and resistance to movement are not currently envisaged, and would require hardware and sensors similar to those on the ReJoyce.

In conclusion, many task-oriented UL tests have failed to transfer from laboratories to everyday clinical practice because of the need to train those who administer the tests, those who rate the tests, long setup and performance times, and difficulties in obtaining standardized test items and keeping them together. The system described in this report offers a novel solution to this unmet need.

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## REFERENCES

Carroll, D. (1965). A quantitative test of upper extremity function. *Journal of Chronic Diseases*, *18*, 479–491.

Catz, A., Itzkovich, M., Agranov, E., Ring, H., & Tamir, A. (1997). SCIM: Spinal cord independence measure: A new disability scale for patients with spinal cord lesions. *Spinal Cord*, *35*, 850–856.

Coderre, A. M., Zeid, A. A., Dukelow, S. P., Demmer, M. J., Moore, K. D., Demers, M. J., . . . Scott, S. H. (2010). Assessment of upper-limb sensorimotor function of subacute stroke patients using visually guided reaching. *Neurorehabilitation and Neural Repair*, *24*, 528–541. doi:10.1177/1545968309356091

Debert, C. T., Herter, T. M., Scott, S. H., & Dukelow, S. (2012). Robotic assessment of sensorimotor deficits after traumatic brain injury. *Journal of Neurologic and Physical Therapy*, *36*, 58–67. doi:10.1097/NPT.0b013e318254bd4f

Fleming, M. K., Newham, D. J., Roberts-Lewis, S. F., & Sorinola, I. O. (2014). Self-perceived utilization of the paretic arm in chronic stroke requires high upper limb functional ability. *Archives of Physical Medicine and Rehabilitation*, *95*, 918–924. doi:10.1016/j.apmr.2014.01.009

Fugl-Meyer, A. R., Jaasko, L., Leyman, I., Olsson, S., & Steglind, S. (1975). The post-stroke hemiplegic patient. 1. A method for evaluation of physical performance. *Scandinavian Journal of Rehabilitation Medicine*, *7*, 13–31.

Gladstone, D. J., Danells, C. J., & Black, S. E. (2002). The fugl-meyer assessment of motor recovery after stroke: A critical review of its measurement properties. *Neurorehabilitation and Neural Repair*, *16*, 232–240.

Gritsenko, V., Chhibber, S., & Prochazka, A. (2001). Automated FES-assisted exercise therapy for hemiplegic hand function. *Society for Neuroscience Abstracts*, *27*, 210–220.

Hamilton, B. B., Laughlin, J. A., Fiedler, R. C., & Granger, C. V. (1994). Interrater reliability of the 7-level functional independence measure (FIM). *Scandinavian Journal of Rehabilitation Medicine*, *26*, 115–119.

Kowalczewski, J. (2009). *Upper extremity neurorehabilitation*. PhD dissertation, University of Alberta, Edmonton. Retrieved from http://hdl.handle.net/10048/755

Kowalczewski, J., Chong, S. L., Galea, M., & Prochazka, A. (2011). In-home tele-rehabilitation improves tetraplegic hand function. *Neurorehabilitation and Neural Repair*, *25*, 412–422. doi:1545968310394869

Kowalczewski, J., Gritsenko, V., Ashworth, N., Ellaway, P., & Prochazka, A. (2007). Upper-extremity functional electric stimulation-assisted exercises on a workstation in the subacute phase of stroke recovery. *Archives of Physical Medicine and Rehabilitation*, *88*, 833–839.

Kowalczewski, J., & Prochazka, A. (2011a). Technology improves upper extremity rehabilitation. In A. M. Green, C. E. Chapman, J. F. Kalaska, & F. Lepore (Eds.), *Enhancing performance for action and perception* (Vol. 192, pp. 147–159). Amsterdam, the Netherlands: Elsevier.

Kowalczewski, J., & Prochazka, A. (2011b). Technology improves upper extremity rehabilitation. *Progress in Brain Research*, *192*, 147–159. doi:B978-0-444-53355-5.00010-5

Krebs, H. I., Hogan, N., Aisen, M. L., & Volpe, B. T. (1998). Robot-aided neurorehabilitation. *IEEE Transactions on Rehabilitation Engineering*, *6*, 75–87.

Krebs, H. I., Krams, M., Agrafiotis, D. K., DiBernardo, A., Chavez, J. C., Littman, G. S., . . . Volpe, B. T. (2014). Robotic measurement of arm movements after stroke establishes biomarkers of motor recovery. *Stroke*, *45*, 200–204. doi:10.1161/STROKEAHA.113.002296

Kurillo, G., Han, J. J., Nicorici, A., & Bajcsy, R. (2014). Tele-MFAsT: Kinect-based tele-medicine tool for remote motion and function assessment. *Studies in Health Technology and Informatics*, *196*, 215–221.

Kurillo, G., Han, J. J., Obdrzalek, S., Yan, P., Abresch, R. T., Nicorici, A., & Bajcsy, R. (2013). Upper extremity reachable workspace evaluation with Kinect. *Studies in Health Technology and Informatics*, *184*, 247–253.

Lang, C. E., & Beebe, J. A. (2007). Relating movement control at 9 upper extremity segments to loss of hand function in people with chronic hemiparesis. *Neurorehabilitation and Neural Repair*, *21*, 279–291.

Lang, C. E., Bland, M. D., Bailey, R. R., Schaefer, S. Y., & Birkenmeier, R. L. (2013). Assessment of upper extremity impairment, function, and activity after stroke: Foundations for clinical decision making. *Journal of Hand Therapy*, *26*, 104–114, quiz 115. doi:10.1016/j.jht.2012.06.005

Lang, C. E., Wagner, J. M., Dromerick, A. W., & Edwards, D. F. (2006). Measurement of upper-extremity function early after stroke: Properties of the action research arm test. *Archives of Physical Medicine and Rehabilitation*, *87*, 1605–1610.

Lange, B. S., Requejo, P., Flynn, S. M., Rizzo, A. A., Valero-Cuevas, F. J., Baker, L., & Winstein, C. (2010). The potential of virtual reality and gaming to assist successful aging with disability. *Physical Medicine and Rehabilitation Clinincs of North America*, *21*, 339–356. doi:10.1016/j.pmr.2009.12.007

Lyle, R. C. (1981). A performance test for assessment of upper limb function in physical rehabilitation treatment and research. *International Journal of Rehabilitation Research*, *4*, 483–492.

Michaelsen, S. M., Dannenbaum, R., & Levin, M. F. (2006). Task-specific training with trunk restraint on arm recovery in stroke: Randomized control trial. *Stroke*, *37*, 186–192. doi:01.STR.0000196940.20446.c9 [pii]

Michaelsen, S. M., Luta, A., Roby-Brami, A., & Levin, M. F. (2001). Effect of trunk restraint on the recovery of reaching movements in hemiparetic patients. *Stroke*, *32*, 1875–1883.

Peckham, P. H., & Knutson, J. S. (2005). Functional electrical stimulation for neuromuscular applications. *Annual Review of Biomedical Engineering*, *7*, 327–360.

Reinkensmeyer, D. J., Pang, C. T., Nessler, J. A., & Painter, C. C. (2002). Web-based telerehabilitation for the upper extremity after stroke. *IEEE Transactions Neural Systems and Rehabilitation Engineering*, *10*, 102–108.

Rosamond, W., Flegal, K., Furie, K., Go, A., Greenlund, K., Haase, N., . . . Hong, Y. (2008). Heart disease and stroke statistics—2008 update: A report from the American Heart Association Statistics Committee and Stroke Statistics Subcommittee. *Circulation*, *117*, e25–146.

Savage, P., Ricci, M. A., Lynn, M., Gardner, A., Knight, S., Brochu, M., & Ades, P. (2001). Effects of home versus supervised exercise for patients with intermittent claudication. *Journal of Cardiopulmonary Rehabilitation and Prevention*, *21*, 152–157.

Spooren, A. I., Janssen-Potten, Y. J., Post, M. W., Kerckhofs, E., Nene, A., & Seelen, H. A. (2006). Measuring change in arm hand skilled performance in persons with a cervical spinal cord injury: Responsiveness of the Van Lieshout test. *Spinal Cord*, *44*, 772–779.

Stein, R. B., & Prochazka, A. (2009). Impaired motor function: Functional electrical stimulation. In A. M. Lozano, P. L. Gildenberg, & R. R. Tasker (Eds.), *Textbook of stereotactic and functional neurosurgery* (pp. 3047–3060). Berlin, Germany: Springer.

Taub, E., Uswatte, G., King, D. K., Morris, D., Crago, J. E., & Chatterjee, A. (2006). A placebo-controlled trial of constraint-induced movement therapy for upper extremity after stroke. *Stroke*, *37*, 1045–1049. doi:01.STR.0000206463.66461.97

Van der Lee, J. H., Roorda, L. D., Beckerman, H., Lankhorst, G. J., & Bouter, L. M. (2002). Improving the Action Research Arm test: A unidimensional hierarchical scale. *Clinical Rehabilitation*, *16*, 646–653.

Van der Lee, J. H., Wagenaar, R. C., Lankhorst, G. J., Vogelaar, T. W., Deville, W. L., & Bouter, L. M. (1999). Forced use of the upper extremity in chronic stroke patients: Results from a single-blind randomized clinical trial. *Stroke*, *30*, 2369–2375.

Van Peppen, R. P., Kwakkel, G., Wood-Dauphinee, S., Hendriks, H. J., Van der Wees, P. J., & Dekker, J. (2004). The impact of physical therapy on functional outcomes after stroke: What's the evidence? *Clinical Rehabilitation*, *18*, 833–862.

Volpe, B. T., Huerta, P. T., Zipse, J. L., Rykman, A., Edwards, D., Dipietro, L., . . . Krebs, H. I. (2009). Robotic devices as therapeutic and diagnostic tools for stroke recovery. *Archives of Neurology*, *66*, 1086–1090.

Yozbatiran, N., Der-Yeghiaian, L., & Cramer, S. C. (2008). A standardized approach to performing the action research arm test. *Neurorehabilitation and Neural Repair*, *22*, 78–90. doi:1545968307305353

Zariffa, J., Kapadia, N., Kramer, J. L., Taylor, P., Alizadeh-Meghrazi, M., Zivanovic, V., . . . Steeves, J. D. (2012). Relationship between clinical assessments of function and measurements from an upper-limb robotic rehabilitation device in cervical spinal cord injury. *IEEE Transactions Neural Systems and Rehabilitation Engineering*, *20*, 341–350. doi:10.1109/TNSRE.2011.2181537

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