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Fully-Automated Test of Upper-extremity Function

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Abstract—**With the advent of new approaches to upper extremity recovery after stroke and spinal cord injury, the quantitative evaluation of hand function has become a crucial component of outcome evaluation. Recently we developed a workstation, the ReJoyce (Rehabilitation Joystick for Computer Exercise) on which subjects perform a variety of movement tasks while playing computer games. An important feature of the system is the ReJoyce Automated Hand Function Test (RAHFT). In this study we compared and validated the RAHFT against two widely-used clinical tests, the Action Research Arm Test (ARAT) [1][2] and the Fugl-Meyer Assessment (FMA) [3]. All three tests were performed in 34 separate sessions in 13 tetraplegic individuals. Principal component and regression analyses revealed that both the ARAT and the RAHFT correlated well with the first principle component fitted to the scores of the three tests. The FMA was less well correlated. These data help validate the RAHFT as a quantitative, automated alternative to the ARAT and FMA. The RAHFT is the first comprehensive test of hand function that does not depend on human judgment.**

I. Introduction

A growing body of evidence suggests that intense, task-oriented rehabilitation improves functional outcomes [4]. In recent years several groups have explored ways of automating rehabilitation [5] [6] [7], primarily to reduce costs, and more recently, to allow a continuation of tele-supervised rehabilitation exercises in patients' homes after they leave the clinical environment [8] [9].

The exercise tasks performed by patients in the conventional rehabilitation setting tend to be repetitive and boring. In order to maintain patient interest there is an increasing trend to incorporate computer games into treatment protocols [8]. This has been accelerated by the world-wide adoption of the Nintendo Wii into rehabilitation clinics [11] [12]. The Wii allows users to play computer games by moving a hand-held motion sensor. It is useful for practising unloaded motions of the shoulder and elbow but it has no sensors of hand function so even if its motion signals were available for analysis, they would not form a sufficient basis for a quantitative test of arm and hand function. The ReJoyce (Rehabilitation Joystick for Computer Exercise) provides the requisite signals. It is a passive workstation comprising a segmented arm that presents the user with a variety of spring-loaded manipulanda [15]. Each manipulandum is instrumented with one or more sensors, whose signals are fed to a computer. The signals are analyzed with custom software to control computer games and to run the "ReJoyce Automated Hand Function Test" (RAHFT).

For an automated hand function test such as the RAHFT to become clinically accepted, it must be shown to be substantially equivalent to existing clinical tests. The equipment should be affordable and simple to use, with software that provides audiovisual prompts during the test and quantitative results in the form of spreadsheets and printed reports. The purpose of this study was to examine the RAHFT and see how well it correlated with two conventional, clinically accepted hand function tests.

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II. Methods

A. Participants :

Thirteen people aged between 24 and 56 with tetraplegia resulting from a C5-C6 SCI participated in this study, as part of a broader project [15].

B. Procedures :

Three hand function tests were performed in randomized order in single sessions that took place at 2-weekly intervals during the 6-week treatment periods. The three tests were the Fugl-Myer Assessment (FMA), the Action Research Arm Test (ARAT), and the ReJoyce Arm-hand Function Test (RAHFT), described in detail below. The FMA and ARAT tests were videotaped and scored by a blinded, independent rater.

C. Apparatus :

Each of the six manipulanda in the ReJoyce workstation was designed to represent a task commonly encountered in daily life. The spring-loaded arm had 4 degrees of freedom of movement and was instrumented with rotational potentiometers about each joint. The spring loading of the arm provided some elastic resistance to movement and ensured that the manipulanda returned to a neutral position when they were released. The manipulanda 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 door knob with an exposable key-like element, both of which could be independently rotated. The easiest task to perform was to grasp one or both of the horizontal handles. The gripper, the door knob, key and peg, were located above the

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handles in an approximately ascending order of difficulty of use.

We will refer to an individual's workspace as the functional range of motion (fROM). This is the volume of space in which the person is able to perform functional tasks. 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.

A MAKE Controller Kit (MakingThings LLC Ca. USA) in the base of the ReJoyce arm digitized the analog signals from sensors in each component of the manipulandum assembly. The microprocessor sent the information in digital form via a Universal Serial Bus (USB) to a local computer. The information from the sensors was processed by the computer with custom software that computed the coordinates of the arm segments and manipulanda in 3-dimensional space. These various signals were used by the software to control the RAHFT and interactive games.

D. RAHFT:

The RAHFT consisted of three parts: functional range of motion (fROM), grasp, key-grip, pronation-supination tasks and placement tasks (Figure 1). The users (subjects or therapists) initiated the RAHFT software program by clicking on a desktop icon, after which it ran automatically, taking its cues from signals from the ReJoyce device or inputs from the subject's computer keyboard. As the test

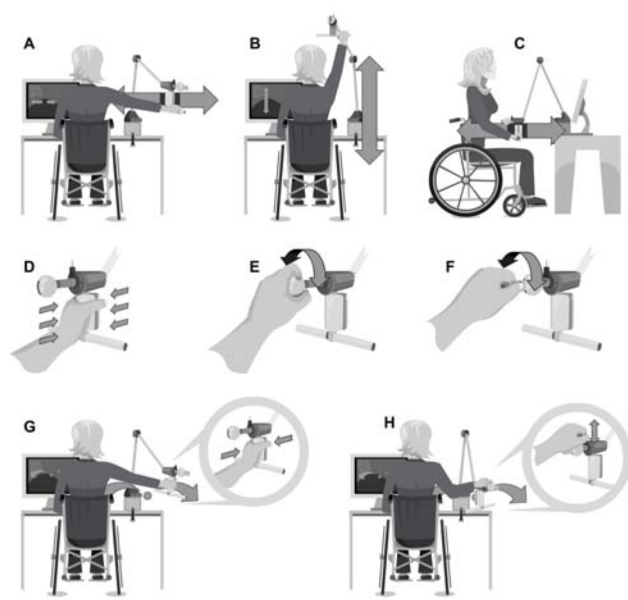

Fig. 1. The ReJoyce system, showing all components of the RAHFT. A) move to left and right; B) move up and down; C) move in and out; D) grasp and squeeze rubber cylinder; E) rotate spring-loaded door-knob; F) rotate spring-loaded key; G) grasp, move and release, using the cylinder; H) pinch peg, lift, move and release.

component of the test with a 3-dimensional animation. The user was then allowed up to 60 seconds 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.

1) fROM. The subject was first asked to hold the horizontal handle on the manipulandum assembly and move it as far to the left and then as far to the right as possible (Figure 1). 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. The spring-loading of the manipulanda 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 manipulandum 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.

3) Doorknob. The subject rotated a spherical, spring-loaded doorknob clockwise and counterclockwise, the mechanism being based on that of commercially available doorknobs.

4) Key. The subject rotated a spring-loaded key-shaped object normally hidden within the doorknob manipulandum (same rotational stiffness as 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. Rotation of the key was then monitored by the software.

5) Placement tasks. The first of these involved picking up a virtual pop can displayed on the computer screen, by holding the gripper loosely, moving it so as to position crosshairs onto the screen image of the pop can, squeezing the gripper to "hold" the virtual can and move it to a position over one of two virtual "garbage bins" located on each side of the screen. The virtual pop can was then dropped into the bin by releasing the gripper. A new virtual 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. In both placement tasks, if the object was not dropped into the inappropriate receptacle, the task had to be repeated until it was completed successfully or 60 seconds had elapsed.

E. 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. In this case each component was scored in terms of the time to completion according to the equation:

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

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

F. Statistical Methods:

Principal Components Analysis was performed with Matlab v. 7.0.1 (The MathWorks, Natick, Ma) software. Principal components (PCs) were computed from the test scores of all three hand function tests and the same software was used to perform a linear regression of the scores of each individual test with respect to the corresponding values along the axis of the first principal component. Each of the hand function tests had different ranges of possible scores: ARAT 57, FMA 54, RAHFT 100, we converted the raw scores to percentages of the full range for each individual test. This allowed the scores from the three tests to be more easily compared.

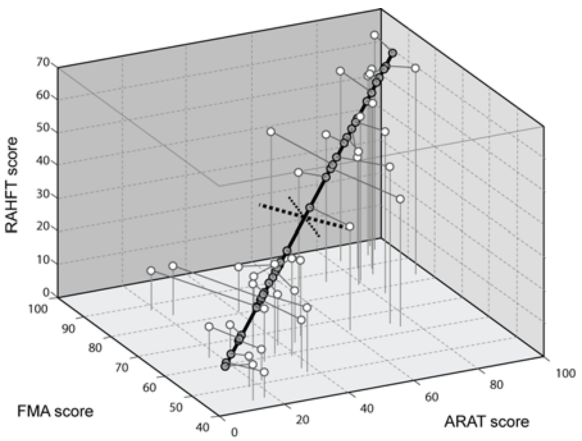

Fig. 2 Principal components analysis of three hand-arm function tests (ARAT, Fugl-Meyer (FMA) and RAHFT) performed on 34 occasions. A) Each yellow point shows the normalized scores of the three tests in a given tetraplegic subject in a single session. The red line is the first principal component (PC1) of the yellow data points, the red dots are the nearest points on PC1 to each data point, with yellow joining lines.

III. Results

The three hand function tests (ARAT, FMA and RAHFT) were performed in randomized order in a total of 34 different single sessions during the 6-week treatment periods with 13 subjects. Figure 2 shows the normalized scores from each session as a data point in a 3-dimensional plot. The first three PCs are shown as orthogonal lines running through the data points in Figure 2. The first PC (PC1), is shown as the long bold line. PC1 accounted for 91% of the variance in the data. The second and third PCs are short, reflecting the much smaller variances of the data in these directions.

Linear regressions were performed, resulting in the following correlation coefficients: ARAT on PC1: r2 = 0.98, FMA on PC1: r2 = 0.64, RAHFT on PC1: r2 = 0.93.

We were interested in validating the RAHFT against the ARAT and FMA. The RAHFT was well correlated with the ARAT (r2 = 0.88), and in fact much better correlated than was the FMA with the ARAT (r2 = 0.53). Not surprisingly in view of these results, the RAHFT and ARAT were only moderately correlated with the FMA (r2 = 0.49 and r2 = 0.53 respectively).

The ARAT took the longest time to administer with a mean time of completion of 7.8 + SD 1.6 minutes), followed by the FMA which took a mean time of 5.2 +1.0 minutes. The RAHFT was performed in the least amount of time, taking a mean of 3.8 +0.90 minutes).

IV. Discussion

The purpose of this study was to see how well the RAHFT correlated with two widely accepted hand function tests, the ARAT and the FMA. In addition to simple regression analysis, principal components analysis was used to quantify the relationships between the three tests. This is a relatively new way of assessing and comparing motor function tests [12] . The RAHFT was highly correlated with PC1 of our data set, as was the ARAT. The FMA was less well correlated. In retrospect, the greater correlation between the RAHFT and ARAT was to be expected, as these tests are designed to assess upper extremity function in ADLs, whereas the FMA primarily focuses on range of motion at individual joints.

Although the ARAT correlated the best of the three tests with PC1, the top end of the range, subjects scored nearly 100% of full scale. Because the corresponding RAHFT scores were less than 70% of full scale, this indicates that the ARAT has a “ceiling effect”. This was supported by the observation that some of the SCI subjects we tested who received near perfect ARAT scores, exhibited visible deficiencies in upper extremity function compared to normal individuals. The FMA also showed a ceiling effect. Thus the ARAT and FMA may be less sensitive than the RAHFT to improvements in high-functioning subjects. At the other end of the scale, 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 reasonably good range of motion., 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.

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 range of motion 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 would be needed 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 inter-rater reliability, validity and responsiveness. Regarding reliability, the advantage of quantification and standardization through automation is that qualitative judgement and rater bias are removed. This eliminates inter-rater variance.

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 [13] and FIM [14]. The RAHFT correlated better with the ARAT (r2 = 0.88) than with the FMA (r2 = 0.49). This was not too surprising, because each component of both the RAHFT and the ARAT was chosen to represent a specific class of ADLs.

The primary function of the ReJoyce system is to serve as a workstation for rehabilitation of upper extremity function. The RAHFT was developed when it was realized that the signals from the sensors allowed us not only to control computer games, but also to quantify performance. The scenario 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 minutes. 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.

In conclusion, many task-oriented hand function 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 and difficulties in obtaining the standardized test items, as well as long set-up and performance times. The system described in this report offers a novel solution to this unmet need.

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