Published in final edited form as:

J Neurosci Methods. 2007 September 30; 165(2): 287–296.

Validation Studies of the Human Movement Analysis Panel for Hand/Arm Performance

Charles D. Smith^{1,2,3,4,*}, Ashley Walton³, John T. Slevin^{2,4,5}, Greg A. Gerhardt^{3,4}, Gloria Umberger², Kyle Smoot³, Emily Schulze³, and Don Gash^{3,4}

1 Department of Biomedical Engineering, University of Kentucky, Lexington, KY-40536

2 Department of Neurology, University of Kentucky, Lexington, KY-40536

3, Departments of Anatomy & Neurobiology, University of Kentucky, Lexington, KY-40536

4, Morris K. Udall Parkinson's Disease Research Center of Excellence, University of Kentucky, Lexington, KY-40536

5 Neurology Service, Department of Veterans Affairs Medical Center, University of Kentucky, Lexington, KY-40536

Abstract

The human movement analysis panel (HMAP) measures separable components of arm motion and simple and complex finger coordination. HMAP testing takes 30 minutes to administer. In separate experiments we have validated the HMAP against the standard grooved pegboard and measures of gait speed, and demonstrated important learning effects over both short durations of days, and longer intervals of months to years in normal subjects of different ages. Stepwise regression demonstrated the strongest correlation between the HMAP complex motor times and pegboard both-hand removal ($R^2 = 0.52$, $p = 0.002$ for dominant and $R^2 = 0.33$, $p = 0.02$ for non-dominant hands). The most consistent and sensitive measure of HMAP motor performance overall was the complex motor time. The HMAP is a short-duration, easily administered, objective quantitative test of motor function, with potential applications in aging, and in Parkinson's Disease and related motor disorders. The HMAP has a smaller version used in primates, so that measurements made in primate models of disease and its treatment are directly comparable to analogous clinical measurements made in the corresponding human disease.

Keywords

aging; motor measurement

* Correspondence to: Dr. Charles D. Smith, Room 62, MRISC (Davis-Mills) Building, University of Kentucky Medical Center, 800 Rose Street, Lexington, KY 40536-0098, Email: csmith@mri.uky.edu, Phone: 859-323-1113, FAX: 859-323-1068

Disclosure Statement

One author (GG) has interest in a company, Quanteon, which makes the HMAP and primate version (mMAP) for interested users. The remaining authors have nothing to disclose. The authors have had no ethical conflicts in the preparation of this manuscript. The authors have not received funding from, and have no other financial relationship with, any commercial organization having a bearing on, or interest in, this manuscript. All of the authors have read and approved the manuscript, and none has a conflict of interest in the research. The manuscript is original not under consideration for publication elsewhere. None of its content including the tables and figures has been published previously.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

1. Introduction

Objective measurement of human motor function is a desirable goal for research into aging and age-related disease, particularly neurologic diseases with pathologic motor features such as idiopathic Parkinson's Disease (IPD). Several quantitative techniques have been used to measure upper extremity movements. These techniques vary in the specific aspect of motor function measured, and include grip and load force variation (Fellows and Noth, 2004;Guo et al., 2004;Hejdukova et al., 2003;Nowak and Hermsdorfer, 2002,2006), finger and thumb movements during day-to-day activities (Sauermann et al., 2005;Simone and Kamper, 2005), timing, velocity and force of finger tapping (Aparicio et al., 2005;Bazner et al., 2005;Kandori et al., 2004;Yahalom et al., 2004), and kinematics of wrist flexion-extension (Byblow et al., 2003), handwriting (Caligiuri et al., 2006) gross arm movement (Byblow et al., 2002;Rand et al., 2002), and reach-to-grasp movements (Hosseini et al., 2000;Jackson et al., 2000;Rand et al., 2006;Tunik et al., 2004;Wenzelburger et al., 2000;Whishaw et al., 2002). Portable and convenient methods measure single aspects of motor function, such as finger bending movements (Sauermann et al., 2005;Simone and Kamper, 2005). Comprehensive methods that capture the complexity of movement (Hosseini et al., 2000;Jackson et al., 2000;Rand et al., 2006;Tunik et al., 2004;Wenzelburger et al., 2000;Whishaw et al., 2002) require specialized equipment or personnel not easily adapted to the clinic, and most have not been used in longitudinal studies to evaluate repeatability and learning effects.

Movement times recorded following computer generated cues that allow simple or two-choice responses have been measured extensively (Gordon et al., 2004;Hayashi et al., 2003;Johnson et al., 2004;Low et al., 2002;Nicoletti et al., 2005;Pinter et al., 1992) and used clinically. Together with finger tapping tasks and the grooved pegboard (Bryden and Roy, 2005), basic movement times are probably the simplest and most time-efficient motor measurement methods for motor quantitation currently in use (Goetz, 2004;Martinez-Martin et al., 1994;Metman et al., 2004). Although these measurements are indeed useful, they cannot be directly compared to those from animal models of aging, Parkinson's Disease or other neurologic disorders with motor features.

We have developed the human movement analysis panel (HMAP), a human-scale version of a device used for motor assessment in primate models of aging and Idiopathic Parkinson's disease (IPD). The HMAP is a portable human motor timing measurement device which records separable components of arm reaching and fine manipulation movements of the hands and fingers. It does not measure muscle forces or directly read out velocities or accelerations. Measurements from the HMAP are directly comparable to those from the primate version (Grondin et al., 2000;Zhang et al., 2000). Previous reports using the HMAP have emphasized the strong effect of age on motor performance speed in both humans (Smith et al., 1999;Smith et al., 2005) and in non-human primates (Grondin et al., 2000;Zhang et al., 2000). This correspondence between the HMAP and the non-primate version may prove useful by measuring the motor effects of experimental interventions in a primate model, then assessing the effect in the human disease using a very similar measure.

In the series of experiments reported here, we focus on the reliability and validity of the HMAP as a quantitative assessment of upper extremity motor performance in humans. We did this by addressing the issue of reliability in longitudinal detection of motor speed differences by performing repeated measurements over varying time intervals ranging from one day to two years, using three independent groups of young subjects and two independent groups of aged subjects. The presence of age-related slowing of motor performance and improved repeat HMAP performance over short intervals has been reported previously (Smith et al., 2005); here we emphasize reliability of the device by demonstrating robust detection in independent groups across a wide range of age and repetition intervals. We also validated HMAP performance by

correlation with an independent measure of hand skill, the Purdue Pegboard, and with an independent measure of overall motor slowing, gait speed. The HMAP has been used extensively in the clinic, and we suggest future ways to modify the HMAP protocol to shorten the time of measurement, an important consideration in clinical applications.

2. Methods

2.1 Subjects

2.1. Normal Subjects—Subjects were recruited from three sources: (1) The longitudinal University of Kentucky Alzheimer's Disease Center (UK-ADC) "biologically resilient adults in neurological studies" (BRAiNS) group (Schmitt et al., 2001), (2) a list of volunteers maintained by the UK-ADRC consisting of healthy aged community dwelling persons who have expressed interest in research studies, and (3) normal young and middle-aged students and staff of the University of Kentucky Medical Center. The BRAiNS group is followed longitudinally with psychometric testing, neurologic examination, and medical review to insure continued normal cognition. The two other normal volunteer groups (aged and young) underwent a brief interview prior to testing to exclude obvious medical or cognitive abnormalities, but did not go through an extensive formal evaluation. The criteria for recruitment for all three groups were generally the same: subjects had to be healthy adults within a specified age range, free of any active medical illness or past neurologic disease. Healthy aged subjects were in the range 60–94 years; young subjects were 19–50 years (details of median age and range are given in each specific study description below). In general "healthy aged" defined for this study means both cognitive normality and the absence of clinical comorbid conditions that would significantly interfere with performance on the HMAP. All subjects remained neurologically normal (e.g., no evidence of stroke or hemiparkinsonism) over the course of the longitudinal portions of the study. Data collection was done under institutionally approved IRB protocols, and informed consent was obtained from all individuals.

2.2 Human Movement Analysis Panel—The HMAP is a portable lightweight device moveable, along with its laptop computer, on a wheeled cart. It can easily be picked up and placed on a desk or table in a clinical examination room (Figure 1).

Testing was performed in a quiet, well-lit room free of noise and other distractions. A short (five minute) interview and demographic questionnaire was administered at the beginning of each session. To avoid fatigue and interference effects, no other testing was performed either before or after any session. HMAP testing was administered identically to the same individual in repeated sessions over time. Subjects were asked to perform the task as quickly and as accurately as possible. All subjects were given the same instruction as part of a script. There was no difference in reward or expectation among sessions and all volunteers participated without payment.

The HMAP consists of a transparent Plexiglas vertical plate with left and right arm portals through which the individual reaches to gain entry to an inner chamber divided into left and right halves (Figure 1). An eye-level blue light signals the individual to start each trial. In separate trials of increasing difficulty, the following four fine motor tasks of hand and wrist were completed within the inner chamber: (1) simple removal from the chamber platform of a 5/16" nut (difficulty level 1), (2) removal of the nut from a 3" straight vertical 1/4"-diameter Plexiglas rod (difficulty level 2), (3) removal of the nut from a curved "question mark" shaped rod (difficulty level 3), and (4) removal of the nut from a multi-curved "double-S" shaped rod (difficulty level 4). The rods are unthreaded and smooth, and the nut slides easily over the rods with minimal resistance. The trial ends when the individual removes the tested arm and hand completely from the entry portal.

At the arm portal and inner chamber openings, light-emitting diode detectors were used to generate timing signals from light beam interruptions generated during the motor tasks. This circuitry was interfaced to a notebook computer equipped with in-house written software allowing automatic measurement of: (1) the interval spent within the inner chamber (chamber time), (2) the total interval spent within the apparatus but outside the inner chamber on both arm entry and arm exit (arm transit time). These data were automatically entered into a disk file for later analysis.

Test administration followed a set protocol for all individuals. Watches, rings and other potentially entangling items were removed and the hands placed comfortably on a hand template in front of each panel opening. The hand template was used to insure a set distance of the hands from the apparatus for each individual and each trial. A set series of detailed instructions was read to the individual, who was allowed to practice until competent; typically this involved one or two practice trials for each difficulty level. The test administrator triggered each trial with a key press, and all subsequent performance time measurement was automatic. Trials were repeated five times for each task. Delay from key press to start signal (blue light on) was randomly varied by the computer from four to eight seconds to avoid anticipation effects.

2.3 Statistical Analysis

All analyses were performed in JMP 6.0 (SAS Institute, Carey, NC).

2.3.1. Method for Identifying HMAP summary variables—Because multiple measurements are made in the same subjects using the HMAP, it is likely that considerable covariance exists between these measurements. Principal components analysis is a statistical technique for reducing multiple measurements into fewer, more tractable biologically relevant compound variables with reduced common variance. A cross-sectional database of HMAP measurements from 542 normal subjects tested between September 1, 1996 and June 22, 2002 was used. Eleven subjects were excluded because of incomplete data, leaving 531. Of this sample 365 were BRAiNS subjects, 55 were from the aged volunteer group and 111 were from the young volunteer group. Subject ages ranged from 18.7 to 95.1 years (median 72.0 years, interquartile range (IQR) 37.3 years). There were 333 women and 198 men. The dominant hand was identified using a twelve-item handedness inventory; 503 were right dominant and 28 left dominant. A principal components analysis with Varimax rotation was performed on correlations to identify four independent variance factors (Table 1). The HMAP variables were the partitioned trial-averaged chamber time and arm transit times for the dominant and non-dominant hand at each of the four difficulty levels (2 measurements $\times$ 2 hands $\times$ 4 levels = 16 variables). Age at testing was added to this variable list for a total of 17. By using average task performance across the five trials performed at each task level (“trial-averaged”), trial performance effects were ignored in this study. Trial performance times tend to remain stable or decrease across the five trials. This issue is the subject of a previous publication and was not examined further in the present study (Smith et al., 2005).

The strength of the components (factor loadings) contributing to each factor is scaled from zero to one (Table 1, columns 2, 4, 6, 8). To clarify interpretation of the results, the principal components matrix was filtered by setting factor loadings less than 0.5 to zero (Table 1, columns 3, 5, 7, 9). It can be seen from this table that the highest factor loadings (greater than 0.5) form groups with similar values corresponding to separate aspects of the HMAP tasks. The groups are labeled with ones to emphasize this pattern. Factor 1 has equivalent loadings on the arm transit times for all difficulty levels in both the dominant and non-dominant hands (40.3% of variance). This factor thus reflects the gross speed of movement of the hand and arm between the HMAP inner chamber portal and entry portal, and is named “arm speed” to reflect

this interpretation. Factor 2 has equivalent loadings on the time spent within the inner chamber during the hand manipulation task by either dominant or non-dominant hand, but only for the two most difficult tasks of the four levels, and is named “complex motor” to reflect this feature (22.6% of variance). Correspondingly Factor 3 reflects time spent during hand manipulation at the two simple lower difficulty levels (named “simple motor”; 17.0% of variance). Factor 4 is interpretable as age (6.3% of variance).

Factor analysis is an unbiased data-driven statistical data reduction technique to isolate independent sources of variance in a large data set with correlated variables. Factors are uncorrelated, and there are factor loadings of varying weights for most or all of the variables entered. Factors do not reflect any concept of what the HMAP measures. In contrast, we want summary variables to capture easily interpretable aspects of task performance measured by the HMAP. We have therefore used the data-driven factor analysis results to rationally guide the selection of summary variables using Table 1, recognizing that this simplification will result in linear dependence (intercorrelation) between them. These summary variables are identified and defined as follows: (1) “arm speed” – trial average of extremity transit times for all difficulty levels for both hands, (2) “complex motor” – trial average of chamber times for the two higher difficulty levels 3 & 4 for both hands, (3) “simple motor” – trial average of chamber times for the two lower difficulty levels 1 & 2 for both hands, and (4) “age” – the age at HMAP measurement. The use of these selected summary variables reduces the 80 separate measurements made in an HMAP session (five trials, four difficulty levels, two time measurements per trial, dominant and non-dominant hand) to three, simplifying the task of analysis. Age is identified as a fourth summary variable.

This analysis was performed without prior assumptions about what aspects of motor function the HMAP measures, yet the factors identified in the analysis were interpretable as separate components of motor performance: gross movement of the upper extremity, fine motor manipulation of the hand in simple defined activities and fine motor manipulation of the hand in more complex activities. Age but not gender was found to be another independent contributor to HMAP measurements. Once these summary variables were identified, we used them consistently in all the following reported experiments.

2.3.2 HMAP Normal Motor Learning—All study groups described in this section and the subsequent sections 2.3.2 – 2.3.5 represent independently recruited, non-overlapping groups of subjects described generally in section 2.3.1.

A group of 25 young normal subjects underwent repeat HMAP sessions at baseline and at one day, two days, three days, two weeks (average 13.9 days, range 10–18 days) and one month (average 33 days, range 23–41 days) after baseline. There were 13 women and 12 men, with median age of 21 years (IQR 1.0). Repeated measures MANOVA was performed to assess performance differences over time among the six consecutive sessions, on each of the four summary measures (see section 2.3.1), corrected for multiple comparisons (Table 2A; Figure 2A).

In a second experiment to assess whether performance differences observed in the first experiment would be present after an extended period without intervening rehearsal, a second group of 12 young normal subjects underwent baseline HMAP measurement with a single repeat measurement after one month. There were 6 men and 6 women, with median age 21.7 years (IQR 3.3). Repeated measures MANOVA was performed to assess performance differences over time between these two sessions.

To examine performance differences over time in older individuals, a group of healthy aged subjects underwent repeat HMAP sessions at baseline and at one day, two days, three days,

and one week. There were 12 males and 12 females, median age 76.5 years (IQR 11.1). Repeated measures MANOVA was performed to assess performance differences over time between the five consecutive sessions, on each of the four summary measures (see section 2.3.1), corrected for multiple comparisons (Table 2B; Figure 2B).

To examine longer time intervals between measurements in aged subjects, normal subjects ($n = 127$) who had repeat HMAP testing in the interval range 1.0 to 4.8 years (average 2.0 ± 0.6 SD years) were selected from the database of 542 normal subjects. There were 86 females and 41 males in this group, with a median age of 77.0 years (IQR 11.5). Repeated measures MANOVA was performed to assess performance differences over time between the two consecutive sessions (see section 2.3.1) (Figure 3).

2.3.3. HMAP Repeatability—Twenty-two of the subjects used in the principal components analysis had three HMAP panel sessions on the same day to assess repeatability. The median age of this group of 13 women and 9 men was 73 years (IQR 5.0). Repeated measures MANOVA was performed to assess significant differences over time, corrected for multiple comparisons.

2.3.4. Comparison With Grooved Pegboard—Thirty-seven HMAP-tested participants completed testing with the standard grooved pegboard on the same day. There were 17 women and 20 men in this group, with median age 21.7 years (IQR 13.9). The grooved pegboard is a venerable measure of upper extremity motor function and is part of the extended Halsted-Reitan battery (Dikmen et al 1998). In this test subjects place 25 metal pegs into corresponding holes in the pegboard and then remove them with the same hand in two separate timed trials; they then repeat the two trials with the other hand. In a third pair of trials the subject is allowed to use both hands at the same time to complete the placement and removal tasks.

For comparison with the grooved pegboard the HMAP measures were separated into dominant and non-dominant hand performance times. To identify the most salient pegboard times related to HMAP performance, forward stepwise regression was performed separately for each of the HMAP summary variables as the response (dominant and non-dominant complex motor, simple motor, and arm speed), and corresponding dominant and non-dominant peg placement time, peg removal time, both hand placement time and both hand removal time as the regressors in each model.

2.3.5. Comparison With Gait Measurement—A group of 79 healthy aged subjects underwent separate assessment of gait speed independently of HMAP measurement. There were 30 males and 49 females with a median age of 73.8 years (IQR 9.1 years). Gait testing consisted of walking recorded by a video camera with an on-screen timer. Video taping allows a more accurate assessment of gait than simple observation with a stop watch because the tape can be re-run to verify the number of steps taken and the exact time points of initiation and termination of the walking sequence. The subject stands up from a chair, walks 15 feet, turns around, walks back and sits down in the chair. This is repeated five times. The walking test takes about 20 minutes. The tape is rated by an experienced research observer who measures walking speed, arm swing, total number of steps taken, and number of steps taken on the walking turn and the turn-to-sit. The summary variable used here was the trial-averaged product of steps taken and total time during the walking sequence (step-seconds).

Analysis was a standard least squares prediction model with step-seconds as the independent variable and HMAP complex and simple motor times, arm speed, age and gender as predictors. Significance was assessed by t-ratio tests with a threshold of $p = 0.05$.

3. Results

3.1 Summary Variables

Selection of the summary variables is demonstrated in Table 1. The factor analysis (*cf.* section 2.3.1) yielded distinct groupings of performance times under each of the four factors with relatively high factor loadings of similar magnitude. These groupings provide the basis for combining these times by averaging to give summary variables characterizing easily interpretable features of motor performance associated with the HMAP. These features are the separate aspects of positioning movements of the arm and hand before and after entry into the inner HMAP chamber, complex hand manipulation, simple hand manipulation, and age at HMAP. Correlations of these four summary variables with their corresponding factor were 0.91, 0.83, 0.78, and 0.87 respectively. In contrast, none of the intercorrelations between variables and non-corresponding factors exceeded 0.5 (average intercorrelation 0.25). These results show that the summary variables reasonably capture and preserve the main HMAP measurement features extracted from the raw data using principal components analysis.

3.2. HMAP Normal Motor Learning

Results for multiple repeat session HMAP measurements in young and in aged normal subjects are shown in Figure 2 A & B. Table 2A gives the F-values and p-values for the overall time course and for the paired adjacent time points for each HMAP measure in 25 young adults shown in Figure 2A. Similar data for 24 healthy aged subjects is given in table 2B, corresponding to Figure 2B. In the young normal repeat group, complex motor and simple motor times demonstrated significant decreases over the sessions, but arm speed remained constant. The aged group showed a similar decrease in complex motor time, but arm speed decreased and simple motor time remained constant.

The separate group of 12 young normal adults who had a single repeat HMAP one month after baseline also demonstrated a significant learning effect of decreased performance time, but only for complex motor time ($F_{8,2}, p = 0.02$). Simple motor and arm speed showed no between-session time differences (all $p > 0.40$).

Figure 3 shows the motor time courses for the healthy aged group over an average interval of 2.0 years; performance times were significantly decreased on all three measures. Complex motor time decreased by 10% ($p < 0.0001$), simple motor time by 5% ($p = 0.02$) and arm speed by 27% ($p < 0.0001$).

3.3. HMAP Repeatability

When sessions were repeated three times on the same day, there was a trend to increased simple motor time ($p = 0.06$) with repetition; the two remaining summary variables complex motor and arm speed showed no repetition effect on the mean values ($p = 0.46$ and $p = 0.15$ respectively). This was a different result from the decreases in performance times on the complex motor measure when sessions were repeated over days (Figure 4 A–C). Note that because fewer time points were used in the repeated measures analysis for Figure 4 B & C (three points instead of six for young subjects and five for aged subjects), statistical power was relatively decreased. Decreases in simple motor time and arm speed described in section 3.2 were therefore not significant in Figure 4.

Because there were no differences in performance mean times between sessions for two of the three performance variables, and no decreases as expected with motor learning over days, we interpreted variations within these sessions as due to a very small contribution from the HMAP panel itself (tenths of milliseconds), together with a much larger contribution from normal random fluctuations in human effort and attention. Therefore the average coefficient of

variation (standard deviation divided by the mean) was computed for the summary variables as a measure of repeat reliability, given these variations. The median coefficient of variation for the repeat sessions was 7.8% for complex motor (IQR 5.8%) and 4.7% for arm speed (IQR 5.0%). Triplicate error can therefore be expected to be within 5–8% for complex motor time and arm speed over sessions done the same day. Because simple motor time and arm speed demonstrated a trend toward increase over sessions, perhaps indicating fatigue or boredom, a reliable coefficient of variation for this measurement was not calculated.

3.4 Comparison With Grooved Pegboard

The stepwise regression demonstrated the strongest correlation between the HMAP complex motor times and pegboard both-hand removal ($R^2 = 0.52$, $p = 0.002$ for dominant and $R^2 = 0.33$, $p = 0.02$ for non-dominant hands). The other pegboard measures did not enter the model with pegboard both-hand removal. Simple motor times and arm speed were not correlated.

3.5 Comparison With Gait Measurement

The overall prediction model for gait speed (step-seconds) was significant (adjusted $r^2 = 0.33$; F-ratio 8.8, $p < 0.0001$). There was no effect of complex motor time. Simple motor time increased with decreasing gait speed. Age was positively correlated with gait speed, whereas arm speed was negatively correlated. Females had slower gait than males (209 ± 12 vs. 171 ± 15 SEM) despite no difference in age between genders.

The negative correlation between gait speed and arm speed was unexpected. To further explore this relationship we divided arm speed into two components: (1) the time between entry into the apparatus and entry into the inner chamber, a variable we term “target arm speed” because it reflects speed of arm and hand movement toward the chamber for manipulation of the target object, and (2) the time between retrieval of the target from the inner chamber and exit from the apparatus (“exit arm speed”). These two variables were entered in place of total arm speed in the standard least squares model. The overall prediction model for gait speed (step-seconds) was significant (adjusted $r^2 = 0.51$; F-ratio 14.6, $p < 0.0001$). In this model gender, complex and simple motor times were not significant. Target arm speed and age were positively correlated with gait speed, but exit arm speed was negatively correlated (Table 3). Nonetheless target arm speed and exit arm speed were positively correlated ($r^2 = 0.39$, $p < 0.0001$).

4. Discussion

These data demonstrate that the HMAP is a valid, repeatable measure of upper extremity motor performance in humans. The HMAP has face validity because it directly measures movements of the hands and arms during simple, well-defined tasks that are easily understood. Factor analysis shows that the data reliably segregate into components of these tasks allowing a meaningful assignment to measures reflecting complex and simple motor movement of the hands, and arm speed. These measures are repeatable within the same day with a triplicate error of approximately 5–8%. We have validated the HMAP against the standard grooved pegboard. We have also demonstrated important learning effects over both short durations of days and longer intervals of months and even years in normal subjects.

We have used the HMAP in several clinical settings, and the ease of use and small size of the device are advantages in these settings. The HMAP can be placed on a rolling cart and takes up a space equivalent to a portable EKG machine, often used in clinical situations. The software allows the operator to run the measurement procedures with little setup time: the task object is placed in the inner chamber and the date of measurement and the subject’s name, birth date, and gender are entered into the computer; the measurements then proceed automatically after a button press from the operator.

The most consistent and sensitive measure of motor performance was the complex motor time. Complex motor time summarizes the time needed for the hand and fingers to manipulate a nut around curved rods, a somewhat demanding fine motor task. The HMAP should therefore be considered as an objective test of certain critical motor performances of the upper extremities. However, if any test is intended to be repeated to measure the effect of an intervention, it is important to first characterize any test-retest learning effects since these could be misinterpreted as improvements due to that intervention.

We showed that measurable performance improvements occur rapidly on HMAP complex and simple motor measures in young subjects, and less robustly but definitely in complex motor time and arm speed in older subjects, over intervals of days to weeks. Improvement on complex motor time was also seen after a one month interval and a one to four year interval with no intervening practice, suggesting that waiting even this long before re-testing does not exclude learning effects, at least for the most sensitive HMAP performance measure, complex motor time. These learning effects are not present if the HMAP is repeated within the same day, an observation we attribute to interference without motor memory consolidation, the latter a process that requires sleep (Smith et al., 2005). Detection of these effects across age groups and repeat time intervals supports the reliability of the HMAP.

The strong relationship between HMAP complex motor times and pegboard performance validates the HMAP against this motor test. However, unlike the pegboard task, the HMAP separates the motor task into meaningful components of fine versus gross motor movements. We have also shown that the HMAP measures of target and exit arm speed predict an independent measure of overall axial motor function, gait speed. Gait speed decreases as age and target arm time increase, an intuitive result based on the overall slowing of motor function with age. The independence of fine motor manipulation times from gait speed was expected, and demonstrates that these HMAP measures are specific to fine motor performance and not simply a reflection of axial motor (gait) slowing.

The finding of an inverse correlation of exit arm speed and gait speed was therefore surprising, but the strength of the association left little doubt of this effect (t-ratio 8.6, $p < 0.0001$). This finding demonstrates that the assumption that exit arm speed would decrease together with a measure of axial motor speed in the same manner as target arm speed is not valid. Exit and target arm speed are independently coupled to gait speed in opposite ways despite their strong positive correlation with each other. The basis of this difference in coupling between target and exit arm speed to gait speed deserves further study. However, differences in the motor planning and execution of hand transport during an approach to a target to be grasped versus simple removal from the apparatus may underlie this observation.

The data we present here support the use of the HMAP as an objective and reliable tool for the assessment of motor function in humans, provided that critical factors are taken into account, particularly age, gender and the effects of repeat testing. In comparison studies these can be overcome by comparing performance with age-matched controls, by testing parallel groups or by using reference data from re-tested subjects. We feel the sensitivity of the HMAP is an overall advantage, but sensitivity brings with it the detection of ordinary fluctuations in motivation and attention, or possibly of medication effects which may not be of interest, and may represent a potential confound when assessing one or a few subjects.

There are potential limitations of the HMAP in assessing certain neurologic disorders that may combine variable abnormalities of strength, spasticity, and cerebellar incoordination among patients, e.g., stroke may cause severe weakness inappropriate for study with the HMAP. The NIH Stroke Scale or other disability instruments would be better choices in this case. The HMAP may be better applied to neurologic diseases with graded disability e.g., basal ganglia

disorders, system disorders such as amyotrophic lateral sclerosis, primary lateral sclerosis, or spinocerebellar degeneration, or myopathies involving the upper extremities. In some cases the HMAP could be used to follow subjects with a known focal disability of the upper extremities over time. A requirement that may limit some HMAP applications is that the subject must be able to sit freely or be supported in an appropriate chair. Finally, we did not examine possible task order effects on HMAP performance times, because of the added complexity of test administration this would involve. If task order was an important consideration for a particular application of the HMAP, that issue would need to be addressed with further study.

The factor analysis demonstrated equivalent performance between hands in normal subjects. But this might not be true in motor disorders demonstrating asymmetry, such as hemiparkinsonism characteristic of early IPD. Only simple modifications would be needed in the analysis of IPD subjects with unilateral parkinsonism because the HMAP measures hand performance separately for each side, a standard part of the approximately 30-minute HMAP examination. Also based on factor analysis, equivalences between task difficulty at the two highest and the two lowest levels of task difficulty were observed. This creates the opportunity of increasing the number of trials on the highest (double-S, level 4) and second highest (straight rod, level 2) difficulty levels and eliminating the other two levels in future studies, potentially reducing the time of measurement by nearly half. This could enhance the usefulness of the HMAP in clinical trials, where subject time commitment is an important practical consideration.

Acknowledgements

This study was supported by GCRC grant M01 RR 02602.

References

- Aparicio P, Diedrichsen J, Ivry RB. Effects of focal basal ganglia lesions on timing and force control. *Brain Cogn* 2005;58:62–74. [PubMed: 15878727]
- Bazner H, Schanz J, Blahak C, Grips E, Wohrle JC, Hennerici M. Differential pattern of hand-tapping compromise in vascular versus idiopathic parkinsonism: a study based on computerized movement analysis. *Mov Disord* 2005;20:504–8. [PubMed: 15645533]
- Bryden PJ, Roy EA. A new method of administering the Grooved Pegboard Test: performance as a function of handedness and sex. *Brain Cogn* 2005;58:258–68. [PubMed: 15963376]
- Byblow WD, Lewis GN, Stinear JW. Effector-specific visual information influences kinesthesia and reaction time performance in Parkinson's disease. *J Mot Behav* 2003;35:99–107. [PubMed: 12711581]
- Byblow WD, Summers JJ, Lewis GN, Thomas J. Bimanual coordination in Parkinson's disease: deficits in movement frequency, amplitude, and pattern switching. *Mov Disord* 2002;17:20–9. [PubMed: 11835435]
- Caligiuri MP, Teulings HL, Filoteo JV, Song D, Lohr JB. Quantitative measurement of handwriting in the assessment of drug-induced parkinsonism. *Hum Mov Sci*. 2006
- Fellows SJ, Noth J. Grip force abnormalities in de novo Parkinson's disease. *Mov Disord* 2004;19:560–5. [PubMed: 15133821]
- Goetz C. Re: UPDRS: Status and recommendations. *Mov Disord* 2004;19:605. [PubMed: 15133834]
- Gordon PH, Yu Q, Qualls C, Winfield H, Dillon S, Greene PE, Fahn S, Breeze RE, Freed CR, Pullman SL. Reaction time and movement time after embryonic cell implantation in Parkinson disease. *Arch Neurol* 2004;61:858–61. [PubMed: 15210522]
- Grondin R, Zhang Z, Gerhardt GA, Gash DM. Dopaminergic therapy improves upper limb motor performance in aged rhesus monkeys. *Ann Neurol* 2000;48:250–3. [PubMed: 10939577]
- Guo X, Hosseini N, Hejdukova B, Olsson T, Johnels B, Steg G. Load force during manual transport in Parkinson's disease. *Acta Neurol Scand* 2004;109:416–24. [PubMed: 15147466]

- Hayashi R, Hashimoto T, Tada T, Ikeda S. Effects of unilateral pallidotomy on voluntary movement, and simple and choice reaction times in Parkinson's disease. *Mov Disord* 2003;18:515–23. [PubMed: 12722165]
- Hejdukova B, Hosseini N, Johnels B, Ingvarsson PE, Steg G, Olsson T. Manual transport in Parkinson's disease. *Mov Disord* 2003;18:565–72. [PubMed: 12722171]
- Hosseini N, Hejdukova B, Ingvarsson PE, Johnels B, Olsson T. On automatic determination of movement phases in manual transport during the precision grip. *Crit Rev Biomed Eng* 2000;28:237–45. [PubMed: 10999394]
- Jackson GM, Jackson SR, Hindle JV. The control of bimanual reach-to-grasp movements in hemiparkinsonian patients. *Exp Brain Res* 2000;132:390–8. [PubMed: 10883388]
- Johnson AM, Vernon PA, Almeida QJ, Grantier LL, Singarayer R, Jog MS. Screening for Parkinson's disease with response time batteries: a pilot study. *BMC Med Inform Decis Mak* 2004;4:14. [PubMed: 15361256]
- Kandori A, Yokoe M, Sakoda S, Abe K, Miyashita T, Oe H, Naritomi H, Ogata K, Tsukada K. Quantitative magnetic detection of finger movements in patients with Parkinson's disease. *Neurosci Res* 2004;49:253–60. [PubMed: 15140567]
- Low KA, Miller J, Vierck E. Response slowing in Parkinson's disease: a psychophysiological analysis of premotor and motor processes. *Brain* 2002;125:1980–94. [PubMed: 12183344]
- Martinez-Martin P, Gil-Nagel A, Gracia LM, Gomez JB, Martinez-Sarries J, Bermejo F. Unified Parkinson's Disease Rating Scale characteristics and structure. The Cooperative Multicentric Group. *Mov Disord* 1994;9:76–83.
- Metman LV, Myre B, Verwey N, Hassin-Baer S, Arzbaeher J, Sierens D, Bakay R. Test-retest reliability of UPDRS-III, dyskinesia scales, and timed motor tests in patients with advanced Parkinson's disease: an argument against multiple baseline assessments. *Mov Disord* 2004;19:1079–84. [PubMed: 15372601]
- Nicoletti G, Arabia G, Pugliese P, Torchia G, Pucci F, Gambardella A, Quattrone A, Zappia M. Movement time and aging: a normative study in healthy subjects with the "Movement Time Analyzer". *Aging Clin Exp Res* 2005;17:207–10. [PubMed: 16110733]
- Nowak DA, Hermsdorfer J. Coordination of grip and load forces during vertical point-to-point movements with a grasped object in Parkinson's disease. *Behav Neurosci* 2002;116:837–50. [PubMed: 12369804]
- Nowak DA, Hermsdorfer J. Objective evaluation of manual performance deficits in neurological movement disorders. *Brain Res Brain Res Rev* 2006;51:108–24.
- Pinter MM, Hellscher RJ, Nael CO, Riedl E, Schnaberth G. Quantification of motor deficit in Parkinson's disease with a motor performance test series. *J Neural Transm Park Dis Dement Sect* 1992;4:131–41. [PubMed: 1571077]
- Rand MK, Smiley-Oyen AL, Shimansky YP, Bloedel JR, Stelmach GE. Control of aperture closure during reach-to-grasp movements in Parkinson's disease. *Exp Brain Res* 2006;168:131–42. [PubMed: 16307233]
- Rand MK, Van Gemmert AW, Stelmach GE. Segment difficulty in two-stroke movements in patients with Parkinson's disease. *Exp Brain Res* 2002;143:383–93. [PubMed: 11889516]
- Sauermann S, Standhardt H, Gerschlagel W, Lanmuller H, Alesch F. Kinematic evaluation in Parkinson's disease using a hand-held position transducer and computerized signal analysis. *Acta Neurochir (Wien)* 2005;147:939–45. [PubMed: 15999229]
- Schmitt FA, Wetherby MM, Wekstein DR, Dearth CM, Markesbery WR. Brain donation in normal aging: procedures, motivations, and donor characteristics from the Biologically Resilient Adults in Neurological Studies (BRAiNS) Project. *Gerontologist* 2001;41:716–22. [PubMed: 11723339]
- Simone LK, Kamper DG. Design considerations for a wearable monitor to measure finger posture. *J Neuroengineering Rehabil* 2005;2:5. [PubMed: 15740622]
- Smith CD, Umberger GH, Manning EL, Slevin JT, Wekstein DR, Schmitt FA, Markesbery WR, Zhang Z, Gerhardt GA, Kryscio RJ, Gash DM. Critical decline in fine motor hand movements in human aging. *Neurology* 1999;53:1458–61. [PubMed: 10534251]

- Smith CD, Walton A, Loveland AD, Umberger GH, Kryscio RJ, Gash DM. Memories that last in old age: motor skill learning and memory preservation. *Neurobiol Aging* 2005;26:883–90. [PubMed: 15718047]
- Tunik E, Poizner H, Adamovich SV, Levin MF, Feldman AG. Deficits in adaptive upper limb control in response to trunk perturbations in Parkinson's disease. *Exp Brain Res* 2004;159:23–32. [PubMed: 15480587]
- Wenzelburger R, Raethjen J, Loffler K, Stolze H, Illert M, Deuschl G. Kinetic tremor in a reach-to-grasp movement in Parkinson's disease. *Mov Disord* 2000;15:1084–94. [PubMed: 11104190]
- Whishaw IQ, Suchowersky O, Davis L, Sarna J, Metz GA, Pellis SM. Impairment of pronation, supination, and body co-ordination in reach-to-grasp tasks in human Parkinson's disease (PD) reveals homology to deficits in animal models. *Behav Brain Res* 2002;133:165–76. [PubMed: 12110450]
- Yahalom G, Simon ES, Thorne R, Peretz C, Giladi N. Hand rhythmic tapping and timing in Parkinson's disease. *Parkinsonism Relat Disord* 2004;10:143–8. [PubMed: 15036168]
- Zhang Z, Andersen A, Smith C, Grondin R, Gerhardt G, Gash D. Motor slowing and parkinsonian signs in aging rhesus monkeys mirror human aging. *J Gerontol A Biol Sci Med Sci* 2000;55:B473–80. [PubMed: 11034220]

Figure 1. HMAP Apparatus

Illustration of HMAP showing a volunteer reaching through the arm and chamber portals with the left hand to remove a nut from the straight task rod placed in the chamber (difficulty level 2). The four task levels of increasing difficulty are represented by a flat platform (1), straight rod (2), question-mark (3) and double-S (4), each placing a higher demand on fine hand manipulation than the level before it.

Figure 2. Performance on Repeat HMAP

2A: Time course of HMAP performance times in 25 young normal subjects over one month showing decreases due to motor learning. Y-axis is performance time in seconds, X-axis is in days after baseline. Error bars represent SEM. All time courses were significant (cf. Table 2A). **2B:** Time course in 24 healthy aged subjects over one week. The time courses were significant except for simple motor time. Same scale and error representation as 2A.

Figure 3. HMAP Performance Over Years

Baseline and repeat performance times for the healthy aged group. Complex, simple and arm speed motor time decrease in this group over an interval of two years without intervening rehearsal of the tasks. Markers key: complex motor – diamond; simple motor – triangle; arm speed – flat bar. Error bars are SEM.

Figure 4. Same-Day versus Successive Day HMAP Performance

Illustration of performance when the HMAP is repeated three times within the same day, compared to performance when repeated three times on successive days. Note Y-axis scales begin at 0.5 seconds. ** = $p < 0.01$.

4A. Performance times during the same day do not change on the complex or arm speed motor measure, and trend upward slightly on the simple motor measures ($N=22$; median age 73 years, range 61–85 years).

4B. In contrast, subjects of a similar age to those in 4A demonstrate a progressive decrease in complex motor time over sessions repeated on three successive days ($N=24$; median age 77 years, range 67–89 years).

4C. Young subjects show the same pattern of decreased session times over three days as older subjects. Consolidation of motor learning with sleep could account for the observed differences ($N=25$; median age 21 years, range 9–26 years).

Table 1

Factor Analysis

Results of factor analysis for HMAP measurements on 531 normal subjects used to guide the selection of summary variables. Loadings for the five rotated factors on each of the trial averaged performance times is shown in columns 2, 4, 6, and 8. To make variable interpretation more direct and intuitive, summary variables corresponding to each factor used in the analysis were created by setting factor loadings less than 0.5 to 0, and loadings greater than 0.5 to 1 (paired columns 3, 5, 7, and 9; e.g., arm speed corresponds to Factor 1, and so on). The only exception made was to move the NC Level 1 loading from the complex motor to the simple motor summary variable; the loadings were similar for both variables.

Column	2	3	4	5	6	7	8	9
	Factor 1	Arm Speed	Factor 2	Complex Motor	Factor 3	Simple Motor	Factor 4	Age
DC Level 1	0.46	0	0.43	0	0.63	1	0.10	0
DC Level 2	0.24	0	0.40	0	0.82	1	0.13	0
DC Level 3	0.29	0	0.81	1	0.31	0	0.17	0
DC Level 4	0.37	0	0.76	1	0.36	0	0.16	0
NC Level 1	0.54	0	0.49	0	0.50	1	0.10	0
NC Level 2	0.30	0	0.35	0	0.79	1	0.19	0
NC Level 3	0.31	0	0.81	1	0.29	0	0.18	0
NC Level 4	0.43	0	0.72	1	0.36	0	0.15	0
DT Level 1	0.85	1	0.30	0	0.23	0	0.14	0
DT Level 2	0.84	1	0.28	0	0.29	0	0.14	0
DT Level 3	0.83	1	0.24	0	0.29	0	0.10	0
DT Level 4	0.80	1	0.19	0	0.28	0	0.12	0
NT Level 1	0.82	1	0.34	0	0.17	0	0.11	0
NT Level 2	0.84	1	0.32	0	0.27	0	0.12	0
NT Level 3	0.88	1	0.26	0	0.14	0	0.14	0
NT Level 4	0.85	1	0.26	0	0.18	0	0.12	0
Age	0.28	0	0.32	0	0.24	0	0.87	1

Key: D – dominant hand; N – non-dominant hand; T – Arm transit time; C – chamber time; Level – difficulty level.

Repeated HMAP Measurements

2A: Results of six repeated sessions in 25 young normal subjects over one month. F-value and p-value separated by a backslash (/) are given for paired comparisons between adjacent time points. The results of the MANOVA fit for the overall time course for all sessions is given in the last column. Data corresponds to Figure 2A. 2B: Results of five repeated sessions over one week in 24 aged subjects. Data corresponds to Figure 2B.

Table 2

Table 2A.							
Variable	Baseline-Dav1	Dav1 – Dav2	Dav2 – Dav3	Dav3 – Week2	Weeks2 – Month1	Overall	
Complex Motor	15.9/0.0005*	1.9/0.18	2.4/0.13	2.4/0.13	2.5/0.13	8.0/0.0003*	
Simple Motor	0.4/0.55	0.64/0.43	5.3/0.03*	0.0/0.97	0.38/0.54	6.0/0.002*	
Arm Speed	2.9/0.10	0.00/0.96	0.73/0.40	1.2/0.0.29	0.11/0.75	1.4/0.26	
Table 2B.							
Variable	Baseline-Dav1	Dav1 – Dav2	Dav2 – Dav3	Dav3 – Week1	Overall		
Complex Motor	2.8/0.11	9.7/0.005*	0.11/0.74	0.24/0.63	3.4/0.03*		
Simple Motor	0.5/0.48	0.17/0.69	0.44/0.51	0.0/0.87	1.0/0.42		
Arm Speed	1.2/0.29	1.0/0.32	0.07/0.80	0.88/0.36	3.1/0.04*		

Table 3**HMAP and Gait**

Results of standard least squares prediction of gait speed by target and exit arm speed, complex and simple motor time, age and gender. Age and target arm speed were positively correlated with gait speed; in contrast there was a strong negative correlation with exit speed.

Variable	Correlation Direction	t-ratio	p-value
Complex Motor	-	0.26	0.79
Simple Motor	Positive	0.99	0.32
Target Arm Speed	Positive	2.5	0.01
Exit Arm Speed	Negative	8.6	<0.0001
Age	Positive	2.7	0.008
Gender	-	0.41	0.68