Int. Disabil. Studies, **12**, 141–148

Impairment and recovery profiles of sensory-motor function following stroke: single-case graphical analysis techniques

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Accepted for publication: November 1990
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Key words Recovery profiles – Cerebral infarction – Psychomotor performance – Strength – Speed – Tracking

Summary Graphical analysis procedures have been developed to improve interpretation of sensory-motor tests from individual subjects following acute brain damage. The procedures have been applied to 11 unilateral stroke patients assessed serially over 12 months on a computerized quantitative sensory-motor test battery of which grip strength, arm speed, and tracking have been chosen for illustrative purposes. The results indicate that four graphs are necessary to fully demonstrate neurologic impairment and recovery of each sensory-motor function, although fewer graphs would be satisfactory in some applications. Such analyses have proven valuable in the display of serial performance of individual patients but demonstration of impairment and recovery is much more difficult than for group analyses.

Introduction

Longitudinal study of sensory-motor function after acute brain damage should quantify initial and final deficits as well as the rate and pattern of improvement in one or more functions. While statistical analysis of data from groups of patients is a powerful research tool, it can hide important changes in individuals within groups. Heterogeneity of group data can result in striking differences between graphs of individuals.[1] Thus, group data may be of little help in estimating the probable progress of an individual patient. Techniques for interpretation of single-case data are important clinically to quantify neurologic status or follow recovery. This is of particular use in patients with rare conditions.

The literature contains many examples of graphical display of serial function (i.e. 'recovery curves') of individual patients. Many of these have been generated from activities of daily living (ADL) functional measures, such as mobility, transfers, dressing, feeding, and kitchen skills.[2–4] Although these are valuable, improvements may be due to learned adaptive skills and do not necessarily reflect neurologic improvement. Batteries of simple arm and/or leg tests have measured neurologic recovery more directly. Usually these have utilized two- or three-point scales and assessed up to 50 functions, such as strength, range of movement, tone, pain, and hand function.[5–9] Recovery curves derived from batteries of subjective test items have advantages of ease of administration, simple instrumentation (if any),[10] and immunity to practice effect.[1] Conversely, they are not quantitative, are susceptible to observer bias, and suffer from lack of sensitivity, especially at extremes of function.[9]

For many research and clinical applications such ordinal scales are inadequate. Consequently, a variety of quantitative tests have been used to measure the pattern of sensory-motor recovery, including tapping,[11] reaction time,[12] rotary pursuit,[11] pursuit tracking,[13] bimanual tracking,[11] and preview tracking.[14,15] De Souza *et al.*[7] combined ordinal and quantitative approaches with a battery of simple arm/hand tests[10] and a pursuit tracking task, finding general agreement between the two types of recovery curves.

A major difficulty in interpretation of recovery curves is differentiation of normal learning from neurologic recovery — even although distinction between the two is far from clear.[16] Use of the good arm as a control in hemiparetic patients[13] has the advantage of matching, but the assumption that the asymptomatic limb is unaffected may be incorrect.[17] Serial testing of patients and normal control subjects seems ideal,[1] but little is known about the relationship between initial level of performance and extent of improvement.[1,15,18] Analysis of variance of repeated measurements has been used to separate out practice from recovery[12] but is based on the unproven assumption that absolute improvement due to practice is the same in both groups.[1] This assumption was also made by Artiola i Fortuny and Hiorns[19] in calculating 'pure recovery' curves by simply subtracting the normal performance practice curve from that of a neurosurgical group. Jones and Donaldson[15] investigated this question by constructing performance increment (PI) graphs that related changes in performance to the level of previous test scores. They concluded that percentage PI graphs gave more convincing evidence of the presence or lack of neurologic recovery than did absolute PI graphs, even though the latter were more dramatically above normal range for recovering patients.

This paper presents graphical analysis procedures developed and applied to impairment and recovery of a range of sensory-motor functions following stroke. Emphasis is on differentiating recovery from practice and the best techniques for single-case studies.

Method

SUBJECTS

A total of 11 patients were studied. Eight had acute unilateral cerebral infarction (confirmed by CT scan) resulting in contralateral arm weakness but no additional major deficit, other than possible sensory impairment; five had infarcts in the right hemisphere and three in the left. A further patient had an infarct in the right cerebellar hemisphere. The remaining two subjects had moderately impaired right arm function and formed a static stroke control group. They had suffered infarcts 19 and 36 months earlier, so recovery could be reasonably assumed to have plateaued.

There were two normal groups. A single session group comprised 36 subjects drawn from the community and hospital staff, with none having a medical history which could affect sensory-motor function. They were divided evenly by sex and into six age decades between 16 and 75

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years (mean 45·3, range 20 – 72). A subset comprising one subject from each of the 12 age – sex groups formed a multiple session group who undertook a further 10 test sessions.

All subject were right-handed (self-declared), except for one from the static stroke group. All subjects had visual acuities of 6/9 or better in their best eye.

APPARATUS AND TESTS

Quantitative and ADL assessments were carried out serially and in parallel during the study.

System hardware for the quantitative assessment was based around a PDP-11/34 computer running under the RT11 single-user operating system. Test stimuli were displayed on a VT11 dynamic graphics unit with a 279 mm wide × 228 mm high screen. All motor tests used a steering wheel (395 mm diameter) for measuring subject's output, except for grip strength which utilized a 'TEC' grip dynamometer.

Tests comprised three pursuit tracking tasks (random, step, and combination) for measurement of integrated function,[20] and 12 tests aimed at breaking tracking into sensory, perceptual, and motor component functions (visual resolution, object perception, static and dynamic perception, movement sense, range of arm movement, grip and arm strength, reaction time, speed, steadiness, steady movement). Further discussion of these tests is restricted to grip strength, arm speed, and tracking, as results from these ably demonstrate the utility of the graphical analysis techniques.

As details are given elsewhere,[20] only a summary of the tracking tasks is provided. Each task lasted 120 s and subjects were instructed to maintain an arrow point on the input target signal throughout the test. Rotation of the wheel moved the arrow horizontally. In random tracking the input target signal was a random waveform which descended from the top of the screen giving an 8·0 s preview time before reaching the point of an arrow. The task required smooth movements over a 175 degrees range of the steering wheel. In step tracking the target comprised 32 steps which were spatially (magnitude and direction) and temporally unpredictable. The unpredictability of the stimulus and the ballistic nature of the desired response places step tracking at the opposite end of sensory-motor spectrum to random tracking. In combination tracking the stimulus alternately cycled between random and step modes over 11 s cycles. Of a large number of performance parameters obtained, the aggregate mean absolute error from the three tasks — Track (in units of *bits* or 0·29 degrees on steering wheel) — is the only one presented in this study.

Grip strength was defined as the best of three attempts on the dynamometer with arm extended by side. Arm speed was defined as the maximum speed attained over eight attempts in moving the steering wheel through 90 degrees from a stationary start.

The ADL assessment was carried out via an upper-limb subset of the Northwick Park index[21] providing a measure of functional activity directly related to everyday tasks. Each of the 11 upper-limb activities were scored on a three-point scale and covered dressing, bathing, washing, toileting, cleaning teeth, grooming, transfer from floor to chair, preparation of food, making tea, using taps, and feeding.

EXPERIMENTAL PROCEDURE

The acute stroke, static stroke, and multiple-session groups underwent 11 tracking sessions spaced exponentially over 1 year — weeks 1, 2, 3, 4, 6, 9, 13, 18, 26, 37, and 52 (in the acute cases, week 1 corresponded to 11 days post-stroke). Grip strength, arm speed, and ADL were assessed only every second session.

All subjects started tests on the first session with their preferred arm. For normal subjects this was their dominant right arm, whereas for patients it was their asymptomatic arm (acute group: R = 5, L = 4; static group: L = 2). The starting arm was alternated in subsequent sessions to prevent order effects confounding inter-arm comparisons.

Graphical analysis techniques

NEUROLOGICAL RECOVERY: CHOICE OF PERFORMANCE INCREMENTS

Choice of the most appropriate measure of improvement in performance — performance increment (PI) — is central to the problem of differentiating neurologic recovery from improvement due to practice. From preview tracking in brain-damaged subjects, Jones and Donaldson[15] empirically concluded that percentage improvement in performance (PIP) graphs gave more reliable evidence of neurologic recovery than absolute improvement in performance (PIA) graphs, as the latter were prone to show false recovery. A more formal investigation was undertaken to help determine optimal increments for tracking and component tests.

Several factors require consideration in choosing the most appropriate PI for a particular function. Firstly, a PI should measure changes with respect to *record* performance from previous test sessions, so that a positive PI implies a new record improvement. Alternative use of the immediately previous performance as reference can be misleading as a large apparent improvement following a bad performance is not necessarily an overall improvement. Secondly, a PI should be independent of absolute level of performance. Thus, on the basis of learning abilities being no greater than normal, static stroke subjects should, at best, produce the same practice PIs as normals, irrespective of initial performance levels. If this was not the case, an improvement in error score of 100 to 90 might be incorrectly reported as evidence of recovery whereas, at least in the case of tracking, it is no different from a change of 10 to 9 in a normal subject — both represent 10% improvement. Conversely, in the case of functions in which there is no practice component, this factor can be ignored. Thirdly, improvements from zero performance are valid only for absolute increments (e.g. a PIP from zero performance is infinite). Fourthly, as PIPs are normalized (i.e. having no absolute units) they are more comparable with different measures and preferred to PIAs.

PIAs are more appropriate for grip strength and arm speed as they may start from zero performance and neither have any significant practice effect.[22]

All three tracking tasks showed major practice effects[22] necessitating investigation of the effect of absolute level of performance on PIs. Scatter plots were generated of absolute and percentage increments at Session 2 against scores on Session 1. A plot with a horizontal linear regression line (= zero correlation) and a reasonable data fit would show independence between increments and levels of performance. Neither the right nor the left arm PIP was correlated with initial performance on Track ($r = 0 \cdot 09$; $r = -0 \cdot 13$), whereas the corresponding PIA correlation for right arm was significant ($r = 0 \cdot 60$, $p < 0 \cdot 05$; left arm $r = 0 \cdot 16$). Hence PIPs are superior measures of tracking increments.

The superiority of PIPs for tracking was further confirmed by the average Track scores of static stroke patients. One subject's 11-session PIA of 1·35 for the asymptomatic arm was within the normal range (0·62 – 1·75) whereas 3·15 for symptomatic arm was well above it. This might have been incorrectly interpreted as evidence of neurologic recovery in an acute stroke patient. However, corresponding PIPs of 4·71 and 4·68 were essentially equal and within the normal range (2·00 – 5·23).

In summary, PIAs were the most appropriate PIs for grip strength and arm speed due to minimal practice and suitability for zero performance scores. Investigation of normal and static stroke groups demonstrated that PIPs were superior for tracking as they minimized the influence of performance levels.

FIVE GRAPHS PER FUNCTION

The study of impairment and recovery in single acute stroke subjects was based around five graphs for each quantitative sensory-motor measure. The graphs are of raw scores (*Performance*), record performances (*Record*), record increments (*Record Increment*), differential of records between the two arms (*Differential of Records*), and differential of record increments between the two arms (*Differential of Record Increments*). These are described in Table 1 and are based on the following concepts:

Three further considerations apply to the plotting of certain functions. Firstly, as normal subjects have perfect (ceiling) scores on measures such as ADL, graphs additional to Performance are no value. Secondly, if normal male – female differences were substantial (>15%) at the final session, the sexes were subgrouped. Thus, grip strength (36%) and speed (18%)[22] have smaller ($n = 6$) male and female normal baselines. Subgroupings were not necessary for differential graphs as these scores have smaller variations. By the same criteria, subgrouping for age and laterality was not necessary. Thirdly, to partly offset the relatively small number of subjects in the multiple-session normal group ($n = 12$), the mean and range of the larger single normal group ($n = 36$) on Session 1 are included on Performance and Record graphs.

Table 1 Display of individual patient serial data: five graphs per sensory-motor function

Graph	*Definition*	*Feature assessed*	*Interpretation*
Performance	Raw score	Performance	If either arm impaired, Performance scores are below normal range
Record	Best Performance score up to current session	Neurologic status	If either arm impaired, Record scores are below normal range
Record Increment	Change in score relative to previous record; + = Record improvement − = Performance decrement (non-record)	Change in neurologic status (improvement or deterioration)	If either arm improving, Record Increment scores above normal range
Differential of Record	Difference between Records for each arm, i.e. asymptomatic arm is reference	Difference in neurologic status between arms	If symptomatic arm impaired, Differential of Record scores above normal range
Differential of Record Increments	Difference between +ve Record Increments for each arm, i.e. asymptomatic arm is reference	Difference in neurologic recovery between arms	If symptomatic arm improving, Differential of Record Increment scores above normal range

Note. All descriptions are in terms of performance scores; minor changes are required for error scores.

1. Neurologic function does not deteriorate — this assumption seems reasonable in a study of recovery following a single episode of cerebral infarction.
2. 'Off-day' performance does not imply transient deterioration of underlying neurologic status — thus, a graph of record rather than raw scores gives a more accurate and stable representation of neurologic status.
3. Both absolute and increment graphs are necessary — while graphs of absolute scores, whether raw or record, indicate the level of dysfunction relative to normal, they cannot indicate whether improvement is due to practice or neurologic recovery (unless zero practice has been established for the test in normal subjects). Conversely, increment graphs measure improvement, allowing direct comparison with normal practice.
4. Increments must be with respect to record scores — a graph of inter-session changes based on raw scores could be misleading. For example, raw increments from consecutive symptomatic grip strength scores of 30, 30, 20, 30 kg would be 0, − 10, + 10. The last increment could be above that for any normal subject and suggest neurologic recovery whereas strength has only returned to its previous best level following an 'off' performance. Corresponding record increments would be 0, − 10, 0.
5. Differential graphs comparing sides may be more sensitive than absolute graphs — this is especially likely for functions with a wide normal absolute range (e.g. strength) and small differentials between arms.

Results

NORMAL SUBJECTS

Normal results (mean and range) are displayed in the serial graphs of Figures 1 – 3, together with patient data discussed in the next section. There are several features of the normal results which deserve comment and help to illustrate interpretation of the five graph types.

On grip strength (Figure 1) Record Increment indicates a small average improvement on second test (Session 3) but not thereafter. Differential of Records indicates a slight superior strength of right over left hand. On arm strength (Figure 2) Record Increment indicates negligible practice effect and Differential of Records a small right arm superiority. On Track (Figure 3) Performance indicates that average performance has essentially plateaued by the fourth session although smaller improvements continue to be made at the remaining seven sessions. Marked test arm order effect is seen in Differential of Record Increments with right arm improving more than left arm in all cases at session 2, and the converse at session 3. The reduction in size of range between Record and Differential of Records is more for tracking (16% in the final session) than any other function, potentially making Track the most sensitive measure of differences between the two arms.

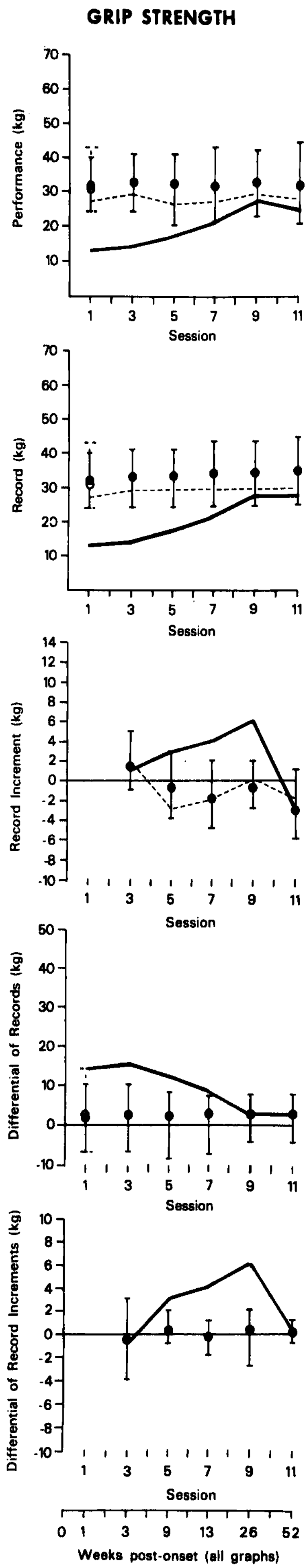


Figure 1 Patient A (moderate acute stroke) on grip strength.

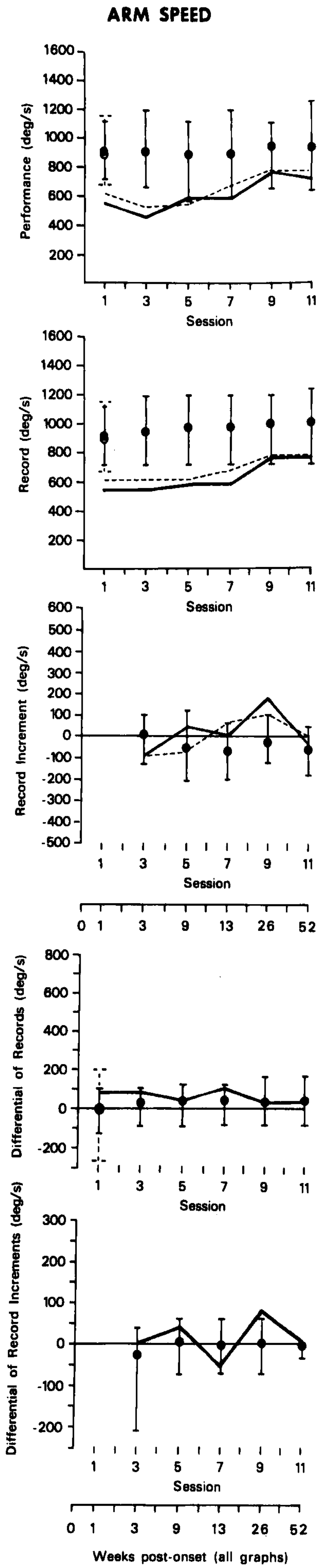


Figure 2 Patient A on arm speed.

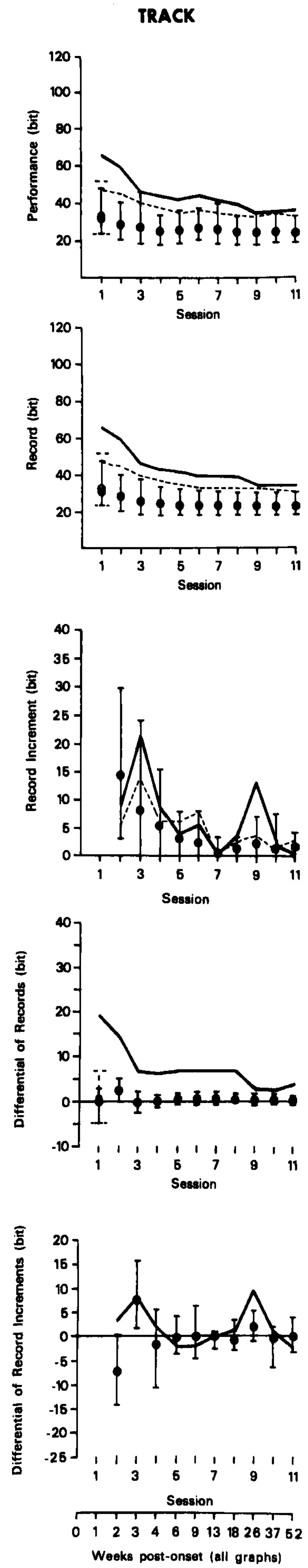


Figure 3 Patient A on Track (aggregate of random, step, and combination tracking).

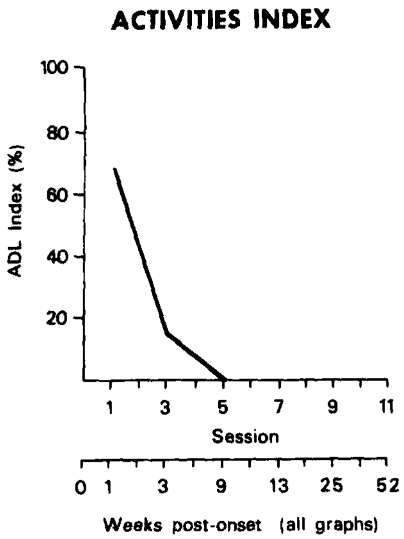


Figure 4 Patient A on activities of daily living index.

SAMPLE PATIENT: GRAPHS AND INTERPRETATION

Figures 1 – 4 show data from a typical subject, patient A, a 61-year-old woman with acute left hemisphere subcortical infarction producing right hemiparesis. Clinical examination demonstrated no sensory or higher mental function deficit. On grip strength (Figure 1) her symptomatic arm was moderately impaired initially but made a nearly complete recovery, most improvement occurring between 3 and 26 weeks (sessions 3 and 9). It was still below normal at 13 weeks (session 7), which was more distinct in Record than Performance. Recovery above practice was seen in both increment graphs at 13 and 26 weeks, but only in Differential of Record Increments at 9 weeks. On arm speed (Figure 2) *both* arms were minimally impaired up until 13 weeks (session 7), with the symptomatic arm being only slightly more affected than the asymptomatic arm. Even at 52 weeks (session 11) both arms were at the bottom of the normal range. On Track (Figure 3) Record and Differential of Records show that the symptomatic arm was moderately impaired but by 52 weeks (session 11) had nearly returned to normal. However, the only recovery above expected improvement with practice was seen in increment graphs at weeks 2 and 26 (sessions 2 and 9). The asymptomatic arm remained borderline throughout. On ADL (Figure 4) a high impairment index of 68% on first assessment days had returned to zero by 9 weeks (session 5).

In summary, following a left subcortical infarct, patient A's right arm was unequivocally impaired on grip strength, arm speed, tracking, and ADL. After 12 months, function was still marginally impaired on speed and tracking in the right and the 'non-affected' left arm. Varying degrees of neurologic recovery in the symptomatic arm were demonstrable on Record Increment and Differential of Record Increments for all functions with largest supranormal improvements seen at 6 months. In contrast, the ADL index was already zero by the 9th week.

INTERCOMPARISON OF THE FIVE GRAPH TYPES

Inspection of serial graphs for the nine stroke subjects highlighted features of the five graph types. These, with examples (given as function plus pertinent sessions), are:

1. Record often gave better separation of the patient from normal data than Performance. Examples – patient A: grip strength, 7; arm speed, 5, 7; Track, 3, 7, 9, 10; patient B: Track, 3, 5, 7, 9, 11 (Figure 5).
2. Differential of Records often showed symptomatic arm impairment not evident in or better than Record. In three patients impairment was evident only in Differential of

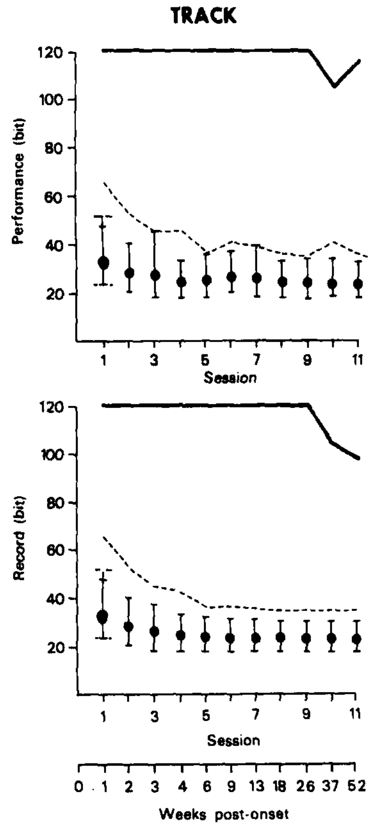


Figure 5 Patient B (severe acute stroke) on Track: an example of superior separation between patient and normal range of Record compared with raw scores (asymptomatic arm was unequivocally abnormal throughout trial in Record but not Performance) and of impairment in asymptomatic arm which would not be seen in Differential of Records.

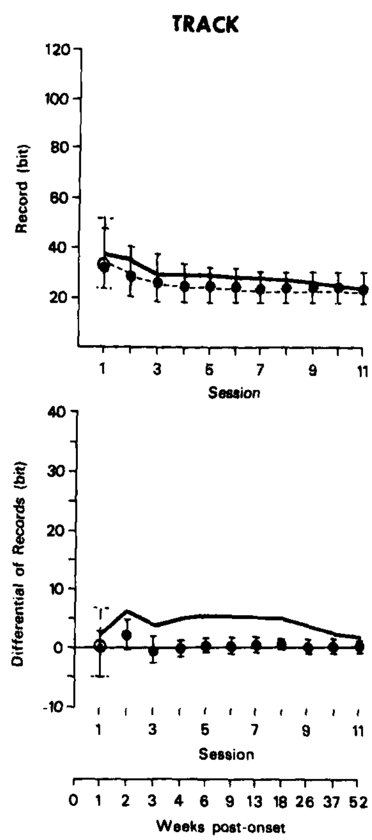


Figure 6 Patient C (mild acute stroke) on Track: an example of greater sensitivity of arm differential in which both arms were well within normal range in Record but symptomatic arm was clearly abnormal relative to asymptomatic arm in Differential of Records.

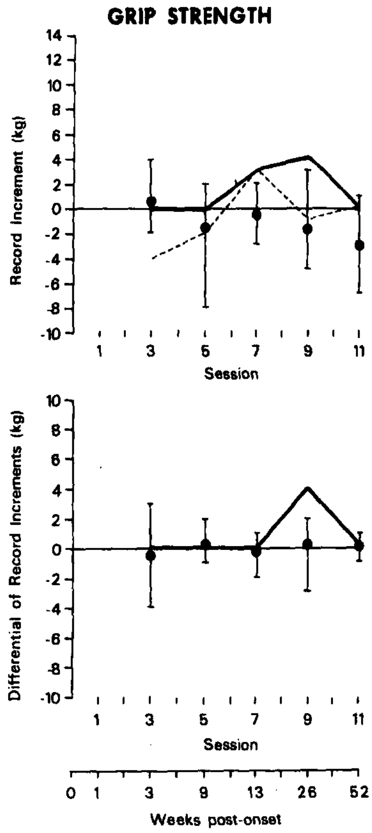
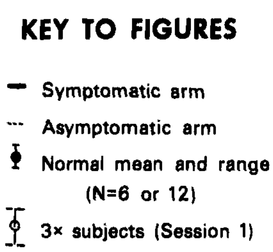


Figure 7 Patient D (severe acute stroke) on grip strength: an example of failure of Differential of Record Increments to show neurologic recovery occurring in either arm at session 7 due to differencing of record improvements seen in Record Increment.



Records and was most striking in Track due to the small side-to-side difference in normals. Examples – patient A: Track, all; patient C: Track, 2..11 (Figure 6).

3. Differential of Records, by definition, could not show impairment in the 'good' arm (or bilateral impairment). In contrast, eight patients showed impairment of the asymptomatic arm in Record on one or more functions. Examples – patient A: arm speed, 1, 3, 5, 7; Track, 2..10 (marginal); Patient B: Track, all (Figure 5).
4. Differential of Record Increments often showed neurologic recovery in the symptomatic arm better than or not evident in Record Increment. This was seen in four patients. Examples – patient A: grip strength, 5; Track, 2.
5. Differential of Record Increments could not show neurologic recovery in the asymptomatic arm, and apparent recovery in the symptomatic arm was reduced where improvement was bilateral. This was seen in three patients. Example – patient E: grip strength, 7 (Figure 7).

OVERALL CLINICAL RESULTS

Following acute unilateral stroke, the ipsilateral asymptomatic arm was impaired in eight of nine patients on one or more functions. Arm speed was most frequently affected (five cases), followed by Track (four), reaction time (three), steady movement (three), grip strength (two), and arm strength (two). On clinical examination no impairment of the good arm was found in any patient.

All patients recovered to some degree in the symptomatic arm and, in most cases, the asymptomatic arm on one or more tests. Only six, however, had Record Increment values on Track sufficiently above normal to suggest unequivocal neurologic recovery and the maximum trial average increment for the symptomatic arm was only 6·9. This is not much above the normal range of 2·0 – 5·2 and, ironically, is slightly less than the maximum value of 7·0 for the asymptomatic arm.

Discussion

Our analytical and graphical procedures enable display, analysis, and interpretation of neurologic status and recovery of sensory-motor function of *single* subjects following acute brain damage. The degree of accuracy and sensitivity achieved reflects the use of quantitative measures (cf. subjective ordinal-scale assessments) and comparisons between patient and control data which minimize the effect of practice and off-day performances.

Four graphs have been found necessary to fully demonstrate neurologic impairment and recovery of each sensory-motor function tested. The important features of these graphs are summarized in Table 2. The fifth graph – raw performance – can be omitted as its information is better displayed, relative to normal baseline data, in the four derivative graphs.

In clinical practice it might not be necessary to use all four graphs in all applications. If, for example, the user's interest was solely in the symptomatic arm, only the two differential graphs need be generated. The overall number of graphs required is also governed by which sensory-motor functions are of interest for a particular patient. This could vary from a single function, such as grip strength, to multiple functions as in this study.

In practice the Northwich Park ADL index bore little relation to the status of affected arm, as it is possible to achieve a perfect score using the non-affected arm alone. In retrospect this index was clearly inappropriate for the role of a parallel ADL measure of disability in the affected arm. It may have been more relevant if assessment had been restricted to the symptomatic arm only.

Serial graphical analysis of single cases allows display of individual profiles but it is much more difficult to demonstrate unequivocal impairment and recovery than in group analysis.[17] For scores to indicate impairment in an individual they must be below normal range, whereas in the group case the mean score could indicate a statistically significant deficit but still be well within the normal range. Similarly, demonstration of neurologic recovery in a patient requires that performance increments are greater than the maximum increment of any normal subjects. Notwithstanding these difficulties, it was possible to demonstrate and quantify deficits in the single-case situation which were not detectable on clinical examination.

General sensitivity of the quantitative tests and associated analysis procedures was best demonstrated by deficits of sensory-motor function in the arm ipsilateral to the lesion in seven of eight patients following unilateral cerebral infarction. In contrast, clinical examination detected no asymptomatic arm deficit in any patient. Functions most affected – such as speed, tracking, and reaction time – probably depend on both cerebral hemispheres. Overall impairment of strength, reaction time, speed, steadiness, steady movement, and tracking has also been demonstrated in the asymptomatic arm of these patients for up to 12 months post-stroke.[17]

Table 2 Summary of advantages and disadvantages of the five graph types.

Graph	*Advantages*	*Disadvantages*
Performance	Contains all raw patient information	Cannot show certain information on normal data: arm differentials, full effect of practice, whether bottom of normal range indicates the worst record performance or only an off-day score
		Less able to demonstrate dysfunction and recovery in patients
Record	Better discrimination between normal and abnormal function than Performance due to removal of off-days	Cannot show neurologic deterioration
	Superior discrimination between symptomatic and asymptomatic arms	
Record Increment	Clear distinction between record improvements and plateauing	Neurologic recovery in unequivocal only if Record Increment is greater than maximum Record Increment due to practice in any one of normal subjects
	Shows neurologic recovery and deterioration	
Differential or Records	May show impairment in symptomatic arm even though within Record normal range	Cannot show impaired function in asymptomatic arm, or bilateral improvement
	Greater independence from good and bad days (bilateral changes are removed)	Degree of impairment in symptomatic arm is reduced by impairment in asymptomatic arm
		No indication of absolute level of function in either arm
Differential of Record Increments	May show recovery in symptomatic arm even though within Record Increment normal range	Cannot show recovery in asymptomatic arm
		Recovery in symptomatic arm is understated if coincident with improvement in asymptomatic arm
	Improvement due to practice is removed (assuming it is same for both sides)	Cannot show decline in performance as this would be unable to be distinguished from improvement in the other arm

The graphical analysis techniques described in this paper, together with quantitative tests of sensory-motor function, provide a powerful tool for investigating neurologic status and recovery in individual brain damage. They are of particular value in helping separate genuine recovery from normal learning. The utility of these procedures will be enhanced by the establishment of a larger base of longitudinal data on normal subjects, the use of percentiles rather than ranges for such data, and further experience gained from application of the procedures in both clinical and research environments.

Acknowledgements

We would like to thank Mr Peter Waddell for neuropsychologic screening of the patients in this study. Grateful acknowledgement is extended to the patients and control subjects for their willingness to participate in an intensive longitudinal study. This research was supported by the Canterbury Medical Research Foundation, Accident Compensation Corporation, and the Canterbury Area Health Board.

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