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Impaired Touch Discrimination After Stroke: A Quantiative Test

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The ability to discriminate differences in tactile stimuli, such as textures, is commonly and characteristically impaired after stroke. Assessment of tactile discrimination is currently compromised by measures that are not quantitative and standardized, do not assess active touch sensibility, or are not suitable for use in clinical settings with stroke patients. Therefore, a test that addressed these limitations was developed. The Tactile Discrimination Test required subjects to discriminate differences in finely graded plastic ridged surfaces using a three-alternative forced choice design. Test-retest reliability, based on a sample of 35 stroke patients, was high ($r = 0.92$), and changes of the magnitude of 27 percent spatial increase (PSI) can be detected with 95 percent confidence, which is sufficiently accurate for clinical monitoring. A matched pairs study of 50 stroke and 50 unimpaired subjects found that normal performance scores were contained within the 3–46 PSI range. The conservative criterion of abnormality was defined as 46 PSI, with a zone of uncertainty from 31 to 61 PSI. The test differentiated well impaired performance relative to normal standards. These results support the application of the Tactile Discrimination Test as a quantitative, standardized measure appropriate for testing stroke patients in clinical settings. **Key Words:** Cerebrovascular disorders—Standardized assessment—Somsatosensory—Tactile—Hand.

Discriminative sensory loss is common after stroke (1–3), but is often not detected by routine neurologic measures (3). For example, in a recent study, Kim and Choi-Kwon (3) report that only three of 25 patients diagnosed as having pure motor stroke based on conventional sensory tests had intact discriminative sensation when more quantitative measures were used. Impairment has been associated with most lesion locations (3,4) and may occur bilaterally after unilateral stroke (1–3). In the very few studies that focused specifically on discrimination of tactile stimuli, loss was found in approximately 50 percent of patients (1,3,5). In two of these studies, the test described in this paper (1) and a slightly modified version of this test (3) were used.

Tactile discrimination using the hand is important in exploration of the immediate environment and performance of a range of daily activities, such as feeling for a coin in a pocket, touching to determine if surfaces are flush, judging the qualities of fabrics, holding a cup, and manipulating eating implements. Loss of haptic tactile discrimination is important in its own right, but also has detrimental effects on safety (6), sexual and leisure activities (7), spontaneous use of hands (8), motor function (9–12), and reacquisition of skilled movements (13,14). Neurophysiologic investigations have found that grip force varies as a function of surface texture properties (15,16) and that tactile afferent signals are integrated

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Information on availability of the test can be obtained by contacting Dr. Carey.

with automatic motor control to achieve functionally adaptive actions during manipulative phases of grasping (17) and restraint of moving objects (18). Tactile sensibility is also important in perception of surfaces brought into contact with an implement during many skilled activities, e.g., use of utensils in eating and expert application of surgical instruments (19). Finally, hemisensory loss has been found to contribute to inferior independent function and longer periods of hospitalization in several stroke outcome studies [see Carey (2) for review].

The negative impact of somatosensory loss on daily function and rehabilitation outcome, combined with the high prevalence of the loss, highlights the importance of adequately identifying and treating this impairment. Specification of the nature of sensory impairment that may underlie performance of everyday tasks has important consequences for selecting the most appropriate form of treatment and evaluating outcome. For example, after stroke a person may be observed to frequently drop objects. Clinicians may assume that this is due to motor impairment. Given the central role of touch sensation in control of pinch grip and slip detection (15), the disability could be due to impaired touch discrimination. Functional measures alone necessarily confound sensory phenomena with other effects (e.g., motor and cognitive). They need to be systematically supplemented with problem-specific measures to increase sensitivity (20). Also, the impact of intervention may well be positive in sensory terms, but may fail to demonstrate a change in functional tests. This is because the quantity of sensory improvement necessary for measurable gain in functional tests is at present unknown. Quantitative sensory measures are needed in clinical settings to assess the magnitude of change over time so that treatment effectiveness can be objectively evaluated and scientific documentation of outcome can be provided for consumers.

Review of Measures of Tactile Discrimination

Quantitative tests of touch sensibility that may be employed clinically are touch-pressure monofilaments (21), mechanical touch-pressure aesthesiometers (22–24), two-point discrimination tests (25,26), and point localization tests (23,27). Although these tests are quantitative, they are administered statically to a passive hand. In contrast, it is well known that tactile perception is enhanced when there is tangential movement between the skin and a textured surface (28,29). Performance scores for monofilaments and static two-point discrimination tests do not correlate well with return of hand function (26,30), and problems associated with application of the stimuli have been identified (25), particularly when used with stroke patients (2). Although it has been recently argued that testing with WEST-Hand monofilaments does permit controlled force application and is predictive of performance on functional tests requiring tactile discrimination, the authors also emphasize that abnormal touch thresholds cannot be changed with re-education and that standardized tests for texture discrimination are needed (31). Two additional tests that quantify ability of the tactile system to detect a stimulus, but are more dynamic in nature, are the Depth Sense Aesthesiometer (32,33) and the automated gap-detection test (34). These tests have the advantage of measuring tactile sensitivity thresholds using active finger movement, but they are not readily available and are not typically used with stroke patients in clinical settings. Focus of assessment following central nervous system lesions should be on how the stimulus is perceived and interpreted, rather than on abnormal static touch thresholds (2,3). Evaluation of discriminative sensibilities incorporates this emphasis and has the advantage of being more directly related to how we use our somatosensory system in daily activities.

Tests of tactual object discrimination involve active touch perception and are generally accepted as indexes of functional sensibility (26,30). Available tests include the "Moberg pick-up test" (35) and its modified version (36); coin identification test (37); the Manual Form Perception Test (38); discrimination of spheres, rectangles, and cylinders with quantified microgeometric and macrogeometric object properties (26,39); and identification of common multidimensional objects (40). Although these tests are functionally orientated, they require independent, controlled manipulative function (41), which is often lacking in stroke patients. Also, there has been argument over whether astereognosis is a modality-specific disorder or a higher perceptual disorder that could occur when sensation is intact (42), potentially confounding the measurement of tactile discrimination.

Texture discrimination tests also measure dynamic aspects of the tactile system and are functionally orientated. Lederman (28) argues that the perception of texture is a task that can be validly used to examine many of the limitations and capabilities of the tactile system. Texture dimensions are particularly salient in the tactile system and are readily encoded (43). Tactile exploration of textured surfaces involves dynamic touch perception, which can be achieved even by stroke patients who have limited motor control when the surface is moved relative to the fingerpads. Lateral motion of the skin across the textured surface, regardless of the mode of touch, is the invariant feature of the texture exploratory procedure (28,41). Fabric, paper, and sandpaper textures have been employed

in some studies (44,45) and are currently used in some clinics (1). However, these stimuli cannot be readily defined and quantified in simple terms by their geometric characteristics (46), they frequently deteriorate with use and are not readily reproduced and graded. Textured surfaces that vary in objectively defined physical dimensions, and are reproducible and durable, have been developed for laboratory studies (47,48). These surfaces consist of specified patterns that vary in their spatial features. Humans have the ability to discern the spatial features of an object by touch, and are particularly adept at doing so with their fingerpads (49). Surfaces such as these therefore have the potential to be developed for use in clinical settings (46,49). The range of textures used to date (47,50) has been mostly limited to determining normal sensibility and relatively mild impairments. Yet stroke patients are also likely to experience severe discrimination impairment and therefore require a wider range in surfaces.

Although some of the clinical and laboratory tests of tactile discrimination reviewed are quantitative and are supported by some validity and reliability data, these measures are not commonly employed by clinicians when testing stroke patients (1,2), nor are they currently available in a format suitable for testing stroke patients. Clinicians currently employ measures that are usually not quantitative, are largely subjective, and there is no standardized assessment procedure or consistent method of recording findings (2,51,52). Clinical measures have been found to be insensitive (1,3) or inaccurate (1) when compared with quantitative standardized measures, such as the test described herein. Although clinical measures may be able to detect gross sensory loss, they are not able to adequately determine the nature and extent of loss or quantify abnormality, and they cannot assess magnitude of change over time. Quantitative sensory testing is clinically important, particularly in patients who show less than very obvious impairment and changes in impairment.

Reliability of the conventional sensory examination is also problematic (51,52). Problems with variable forces of stimulus application, lack of standardized procedures, and subjective interpretation of responses negatively impact the retest reliability of existing clinical tests (2,51). The extent of agreement between assessors has also been found to be poor when clinically testing stroke patients (53–55), even in studies that use standardized test procedures (51).

Normative guidelines are particularly important following stroke, given the potential for ipsilateral somatosensory impairment in addition to the acknowledged contralateral deficit (3,56,57). The presence of an "unaffected" ipsilateral side cannot be assumed or used as a standard of normality in assessment. Rather, normative standards are required to interpret test scores of both the contralateral and the ipsilateral hand of brain-injured subjects. These norms need to be age-appropriate for the typically older stroke population so that an individual's score can be interpreted in the context of what might be realistically expected for healthy subjects of similar age. This is particularly important given evidence of decreased sensitivity with advancing age (58). Despite the importance of such normative guidelines, routine clinical measures do not typically provide this data. The ability to accurately define tactile impairment and determine the effectiveness of somatosensory retraining programs is therefore currently compromised.

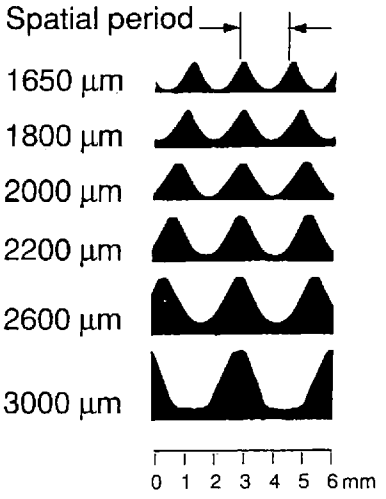
The present study aimed to develop a quantitative, standardized, and reliable measure of tactile discrimination that could be used with stroke patients in clinical and research settings. Texture discrimination was selected because this ability is important for daily functions, it samples dynamic touch perception, it is representative of the discriminative sensory loss commonly experienced after stroke, and it is an important outcome of training, given evidence of task-specific training effects (59). Plastic gratings, originally developed by Darian-Smith and Oke (47), were chosen as suitable texture surfaces because they were objectively and precisely defined by their physical characteristics; quantitative; finely graded; durable and nonabrasive; readily reproducible with precision; could be tactually explored under both voluntary and guided conditions; and, with modification, were potentially suited to clinical assessment of stroke patients. Moreover, the psychometric basis for the surfaces had been well established in neurophysiologic studies with monkeys (47) and psychophysical studies with humans (50). Normative guidelines needed to be established in an age-matched sample to permit adequate interpretation of test scores for the typically older stroke population. Investigation of the capacity of the test to reliably monitor progress over time, and to discriminate between impaired and unimpaired performance, was also required.

Experiment 1: Reliability Study

Method

SUBJECTS

Thirty-five adult stroke patients presenting with a range of somatosensory discrimination skills (normal ability; mild, moderate, and severe impairment), as screened clinically and confirmed with the Tactile Discrimination Test (TDT), were included. Each subject gave voluntary informed consent. Subjects were required to be medically stable; have adequate comprehension



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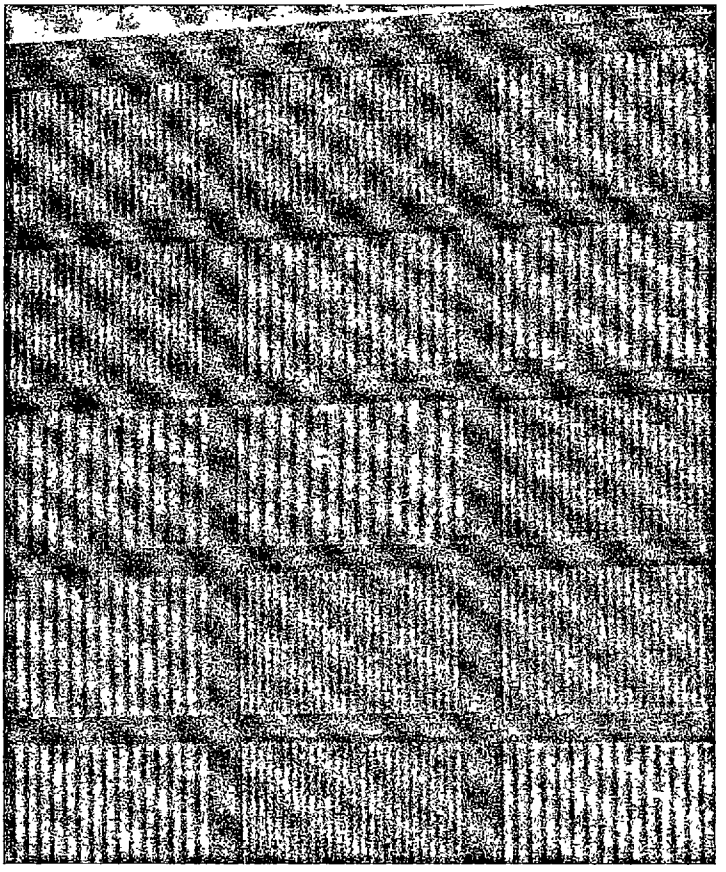

B

Figure 1. Texture gratings employed in Tactile Discrimination Test. *A:* Magnified cross-section of sample of gratings showing spatial period in micrometers. *B:* Example texture plate (largest surface differences) comprising six triplet sets of surfaces (from Carey et al. [59]).

of instructions for assessment; be assessed as free of unilateral spatial neglect using clinical observation and standard neuropsychological tests [shape cancellation (60), line bisection (61), and tactile maze (62) assessments]; and have no peripheral neuropathy. Subjects who met these criteria were selected sequentially as they presented. During selection the range of variation in scores on the TDT was checked to ensure that the full range of texture discrimination skills were sampled. This range was achieved naturally within the sequential selection process. The sample had a mean age of 54 years, ranging from 21 to 79 years (13 years, SD). Twenty-eight subjects were male and seven were female. The right hand was affected in 14 subjects and the left in 21 subjects. Limb position sense was also tested in these subjects using a new quantitative measure (63).

Apparatus

The TDT sampled tactile discrimination ability according to performance on a range of textured surfaces. The test employed finely graded plastic surfaces marked by ridges at set spatial intervals (Figure 1, panel A). Surfaces were produced using a photographic technique that involved exposing a polyamide sheet to ultraviolet light through a prepared negative. Fifteen surfaces with spatial intervals ranging from 1500 µm (micrometer) to 3000 µm were produced, providing a wider range of surfaces than previously available. Ridge-groove ratio was constant. The 3000 µm surface was taken to represent a value near the natural upper limit in the dimension of texture roughness, given evidence of a decline of perceived roughness for spatial intervals greater than 3200 µm (64). The 1500 µm interval is reported to provide a surface in which roughness perception depends on spatial neural coding mechanisms and produces the best match to psychophysical data (65). Differences in spatial period of surfaces ranged from 50 µm to 1,500 mm.

Gratings were designed to be presented in sets of three, with two surfaces identical and one different (Figure 1, panel B). As suggested by Weber's law (66), differences in any given set were defined relative to the anchor 1500 µm stimulus, which appeared in each set. Differences in surface characteristics were expressed as a percentage difference in the spatial periods and varied from 3.33 to 100 percent

spatial increase (PSI). For example, a set containing two 1550 μm stimuli and one 1500 μm stimulus represented a 3.33 PSI difference

$$\left(\frac{1550-1500}{1500} \times 100 = 3.33\right).$$

The 3.33 PSI was selected as a difference that can just be discriminated by neurologically unimpaired subjects (50). Arrangement of surfaces within a set was randomized with respect to position of odd surface, whether it was rougher or smoother, and by how much. Gross, medium, and fine differences between surfaces were provided in three perspex plates. Each plate housed six triplet sets, with some overlap of discrimination levels. The gross plate (Figure 1, panel B) comprised comparison surfaces (relative to the 1500 μm standard) of 3000 μm to 2000 μm, in 200 μm intervals. Comparison surfaces for the medium texture plate ranged from 2200 μm to 1700 μm in 100 μm steps and, for the fine plate, ranged from 1800 μm to 1550 μm, in 50 μm increments. Texture plates slid into the perspex frame of the apparatus to expose one set of surfaces for tactual exploration (Figure 2). Plates were readily positioned and held in place by a self-locking device. A curtain occluded subjects' vision.

Procedure

Following standard instruction, subjects were required to tactually explore the gratings with their preferred finger. Five triplet sets spanning the range of textures (comparison gratings 1550 μm, 1700 μm, 2100 μm, 2600 μm, and 3000 μm) were each presented 10 times in a predetermined random order. Free exploration of surfaces and repetition were allowed. If active finger movement was restricted, the examiner supported the weight of the hand, allowed the preferred finger to rest in an extended position, and, by moving the hand as a unit, guided the finger across the surfaces. The finger was supported only from the side, minimizing application of external downward pressure on textures. In these cases, the examiner attempted to maintain a consistent speed and pressure. Subjects were then required to indicate which texture was different by pointing to or stating the position of the odd texture in each set, according to the forced choice paradigm (66) (Figure 2). No feedback about responses was given during assessment. Testing took 15 to 30 minutes, depending on the subject's physical and cognitive abilities, and was conducted within the subject's concentration span. Rests were provided as required. Responses were recorded as correct or incorrect for each triplet. Probability of correct response for each level of stimulus difference was calculated and standardized using the cumulative normal function (50,67). To calculate the discrimination limen, a straight line was fitted to standardized values using the method of least squares (67). The discrimination limen was the PSI value corresponding to a 0.67 probability of correct response. This method took into account the chance probability of success for each of the stimuli presented.

The hand contralateral to the lesion site, identified by computed tomographic scan and medical history (the "affected hand" in clinical observation), was tested on three separate sessions using the TDT apparatus and standard procedures described previously. Although retest re-

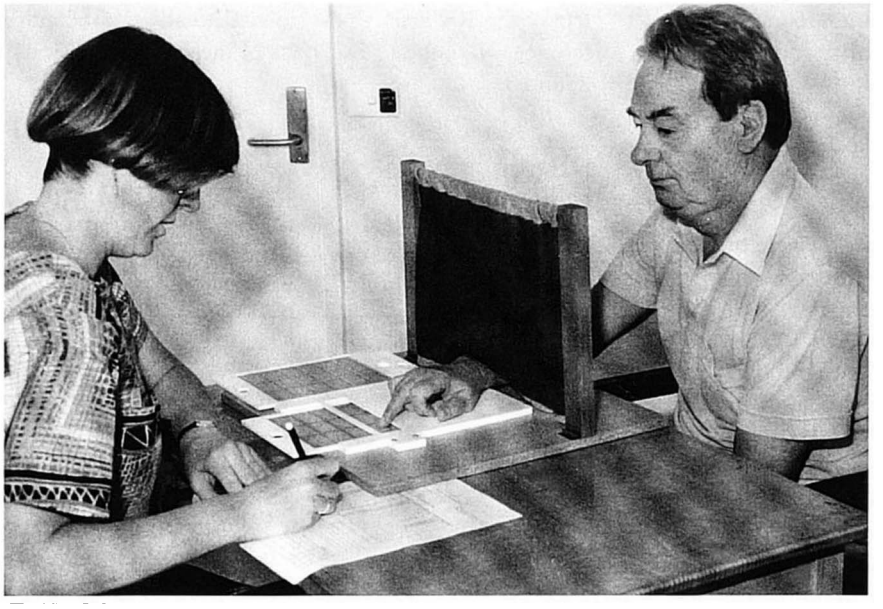

Figure 2. Tactile Discrimination Test: apparatus and testing procedure (from Carey et al. [59]).

liability is typically conducted over two sessions (68), three sessions were employed to permit separate investigation of the error of measurement potentially associated with lack of test familiarity at first assessment. Sessions were usually spaced 24 hours apart, but this interval ranged from 24 hours to 72 hours, depending on subject availability and weekends. This variation seemed acceptable in the context of the temporal course of the condition. The initial test was conducted at least 3 weeks post-stroke to minimize possible influence of early rapid recovery. Potential fatigue associated with testing was minimized by providing rest periods of a few minutes throughout the test sessions. Testing was conducted in a quiet room at approximately the same time of day for each subject. All data were collected by one examiner, the first author. Procedures followed conformed to guidelines of the National Health and Medical Research Council on human experimentation and were in accordance with the ethical standards of La Trobe University Ethics Committee and the ethics committees of participating hospitals.

Data Analysis

Test-retest reliability coefficients (68) were calculated separately for sessions 1 versus 2 and sessions 2 versus 3 to allow for the possibility of serial adaption. Standard errors of measurement (SEM) and 95 percent confidence intervals for estimating a single value (68) and for estimating change in values from one session to another (67) were calculated to obtain metric indexes of combined random and systematic error. The test-retest regression was examined for deviations from the expected slope and intercept parameters of one and zero (69) to investigate systematic errors. Scattergrams around the lines of best fit were also examined for linearity and uniformity in deviations from the regression line.

Results

High reliability coefficients ($r = 0.92$) were obtained for both sets of sessions. The standard error of measurement was estimated to be 9.2 PSI when using sessions 1 and 2 and 8.9 PSI when using sessions 2 and 3. The corresponding two-tailed 95 percent confidence intervals for estimated true scores (χ_t) were $\chi_t \pm 18.7$ PSI and $\chi_t \pm 18.1$ PSI. One-tailed intervals were $\chi_t \pm 15.6$ PSI and $\chi_t \pm 15.1$ PSI. In addition, a reduction in the error of measurement can be achieved by repeating the test and averaging the scores. This reduction can be mathematically predicted from the reliability coefficient and number of tests taken (68, p. 211) as reported in Table 1.

The SEM for estimating change in values from sessions 1 to 2 was 13.4 PSI and from sessions 2 to 3, 12.7 PSI. Mean changes in scores were −2.85 PSI and +0.92 PSI respectively, which were not significantly different from zero. Based on these systematic and random error components, the two-tailed 95 percent confidence interval for estimating a change across sessions 1 and 2 was +24.4 PSI to −30.1 PSI. Across sessions 2 and 3 the corresponding interval ranged from +26.6 PSI to −24.8 PSI.

Scattergrams (Figure 3) showed that the full range of PSI values were represented, although a low density of scores was evident at 75–95 PSI, and suggested the linear model was adequate. However, there did appear to be variation in scatter of scores at different values. Approximately one-third of subjects demonstrated tactile discrimination limens at the ceiling 100 PSI level (indicated by the number of arms on the sunflower in the graphs). These limens were reproduced very accurately. A wider scatter was evident for lower scores, although only three or four points demonstrated substantial variation in each scattergram. This indicated a larger SEM for these lower values. Nevertheless, even at these lower values, average deviation of scores from the line of best fit was calculated to be only 10 PSI.

Inspection of slopes and intercepts suggested no major differences from expected models (Figure 3). This was confirmed by statistical analysis of the regression between sessions 2 and 3. Significant differences from expected slope and intercept occurred in the regression of sessions 1 and 2 (slopes: $t(33) = 2.31$, $p < .05$; intercepts: $t(33) = 2.66$, $p < .02$). These differences in slope and intercept appear to be primarily influenced by data at the lower end of the scale, coupled with the anchoring effect of the 100 PSI values. No statistically significant differences were found by t tests of means from sessions 1, 2, and 3.

Table 1. *Reliability and Standard Error of Measurement (SEM) Associated with Repeated Testing on the Tactile Discrimination Test*

Number of tests	Reliability of averaged scores	SEM of averaged scores (PSI)
1	.920	9.08
2	.958	6.58
3	.972	5.37
4	.979	4.65
5	.983	4.18
6	.986	3.80

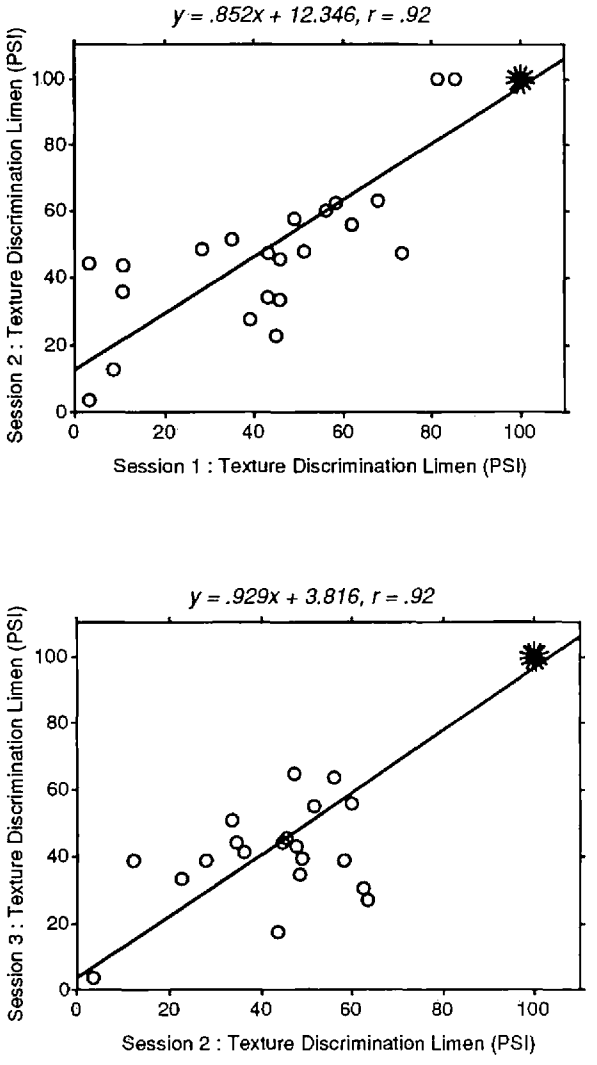

Figure 3. Test-retest reliability scattergrams.

Experiment 2: Normative-Discriminative Study

Method

SUBJECTS

Fifty stroke patients who met the selection criteria outlined for the reliability study were sampled. This group was heterogeneous and included subjects with and without somatosensory loss, as suggested by clinical examination. All patients who met selection criteria and agreed to participate were included. Ages ranged from 21 to 79 years (52 years, mean; 12.6 years, SD). Thirty-four males and 16 females were tested. Six subjects were left-hand dominant and six had inconsistent right or left hand preferences, according to the Annett (70) questionnaire. Subjects were categorized into 5-year age subgroups.

A normative sample comprising 50 subjects without any history of neurologic dysfunction or impairment of sensibility in the upper limbs was also selected. Each subject was individually matched with a subject in the stroke group according to age (within 5-year categories) and sex. Ages ranged from 23 to 77 years (52 years, mean; 13 years, SD). Similar to the stroke group, 34 males and 16 females were tested. Five subjects were left-handed and three were identified as having an inconsistent preference (70). The sample was the same as that involved in the normative-discriminative study of a new quantitative measure of limb position sense (63) and included 33 subjects from the reliability study.

APPARATUS AND PROCEDURE

Each subject was tested bilaterally with the TDT described previously. In the stroke sample, 25 subjects were tested with the "unaffected" hand first, whereas the remaining 25 were tested with the affected hand first. Classification of affected and "unaffected" hands was based on clinical symptoms and diagnostic investigations of site of lesion (e.g., computed tomographic scan), obtained from the medical history of all stroke subjects included in the study. Although some impairment may also be experienced on the side ipsilateral to the lesion (3,57), the common terminology of "unaffected" hand will be adopted to distinguish between the two upper limbs. Data for the dominant and nondominant hands of unimpaired subjects were also collected in counterbalanced order.

Data Analysis

Distribution properties of data from dominant and nondominant hands of unimpaired subjects and affected and "unaffected" hands of stroke subjects were examined with histograms. Criteria of abnormality, defined as the 95th and 100th percentiles of the distribution for unimpaired normal sample, were determined and confirmed with reference to stroke distributions. A zone of uncertainty around these criterion values was constructed using the average one-tailed confidence interval obtained from the reliability study. The one-tailed interval was used as unidirectional decisions are likely to be more frequently employed. Differentiation of impaired and unimpaired performance was also investigated by comparing: the affected hand of stroke subjects with the comparable hand of unimpaired subjects; the "unaffected" stroke hand and matched subject's unimpaired hand; and the affected and "unaffected" hands of stroke subjects. If the affected hand

of the stroke patient was the dominant hand, then the dominant hand of the matched unimpaired subject was selected as the comparable hand for analysis. Differences between stroke and unimpaired subjects and between the dominant and nondominant hands of the unimpaired normal sample were investigated with the Wilcoxon matched-pairs signed-rank nonparametric statistic, as paired difference scores appeared not normally distributed. Age-related differences in performance were investigated using analysis of variance.

Results

Frequency distributions for unimpaired subjects are presented in Figure 4. Mean score for the dominant hand was 19 PSI (11 PSI, SD) and 17 PSI for the nondominant hand (12 PSI, SD). The criterion of abnormality was conservatively placed at the 100th percentile value, 46 PSI. The 95th percentile criterion of abnormality was 34.5 PSI for the dominant hand, 37.7 PSI for the nondominant hand, and 37.3 PSI for the combined distributions. The one-tailed 95 percent confidence interval for estimating an individual score (15 PSI, obtained from the reliability study) yielded a zone of uncertainty of 30 PSI around the criterion of abnormality. Factors that could potentially influence performance of normal subjects, such as hand dominance and age, did not demonstrate statistically significant effects.

Comparison of discrimination limens obtained for the affected hand of stroke subjects and the corresponding hand of matched healthy volunteers (Figure 5, panels A and B) clearly indicated presence of impairment after stroke ($z_w = -5.5$, $p < .001$). In fact, the distribution was skewed in the stroke sample and the modal value was the maximum scale value, 100 PSI (Figure 5, panel A). In contrast, the distribution for the corresponding hand of the unimpaired sample showed opposite skew, with tied modal values in the 0–5 PSI and 20–25 PSI class intervals (Figure 5, panel B). The subgroup of stroke patients with affected hands classified as unimpaired had scores spread across the full normal range. The mean for this unimpaired subgroup of scores was 21 PSI (12 PSI, SD). The mean of the matched sample of neurologically unimpaired subjects was 18 PSI (12 PSI, SD). Discrimination limens for the apparently unaffected hand were also clearly differentiated from those of the corresponding hand of the matched unimpaired sample, as demonstrated visually (Figure 5, panels C & D) and confirmed statistically, using a one-tailed level of probability ($z_w = -3.5$, $p < .001$). Distribution properties of the affected and "unaffected" hands of the stroke sample were also different (Figure 5, panels A & C) and confirmed statistically ($z_w = -4.9$, $p < .001$).

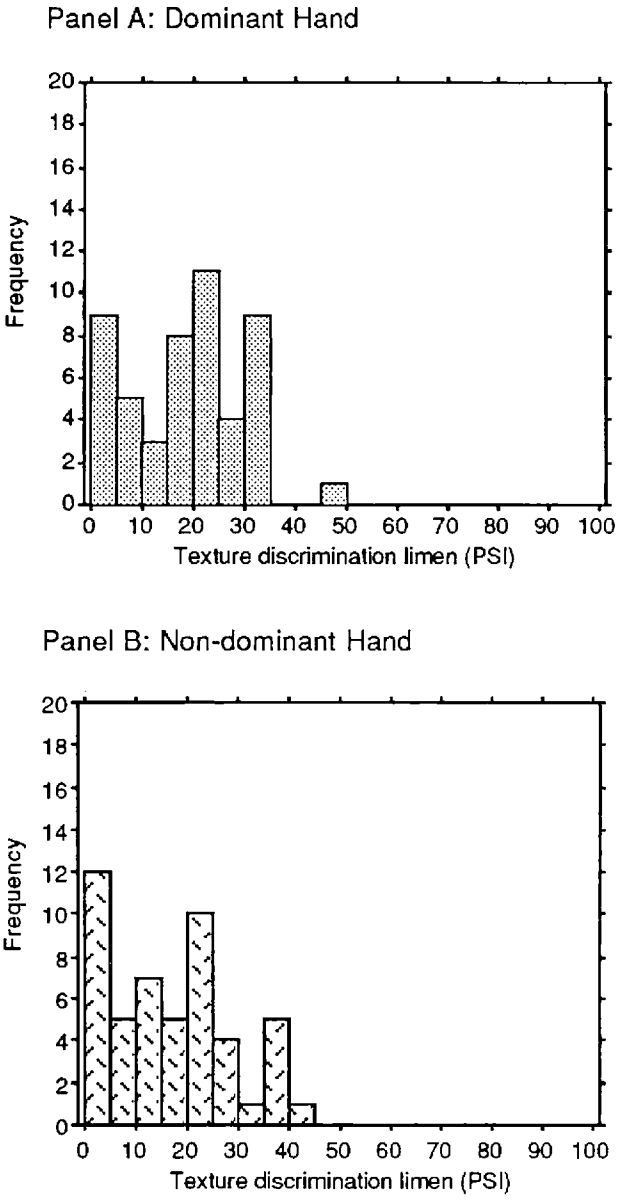

Figure 4. Frequency distribution of texture discrimination limens for dominant and nondominant hands of neurologically unimpaired sample.

Discussion

This study demonstrates a functionally orientated test of tactile discrimination with several advantages over existing clinical assessments, including quantitative scale, standardized scores, reliability and ability to discriminate presence of impairment. Support for the TDT as a valid measure of tactile discrimination has been provided by psychophysical and neurophysiologic studies that employed similar stimuli, dynamic methods of exploration,

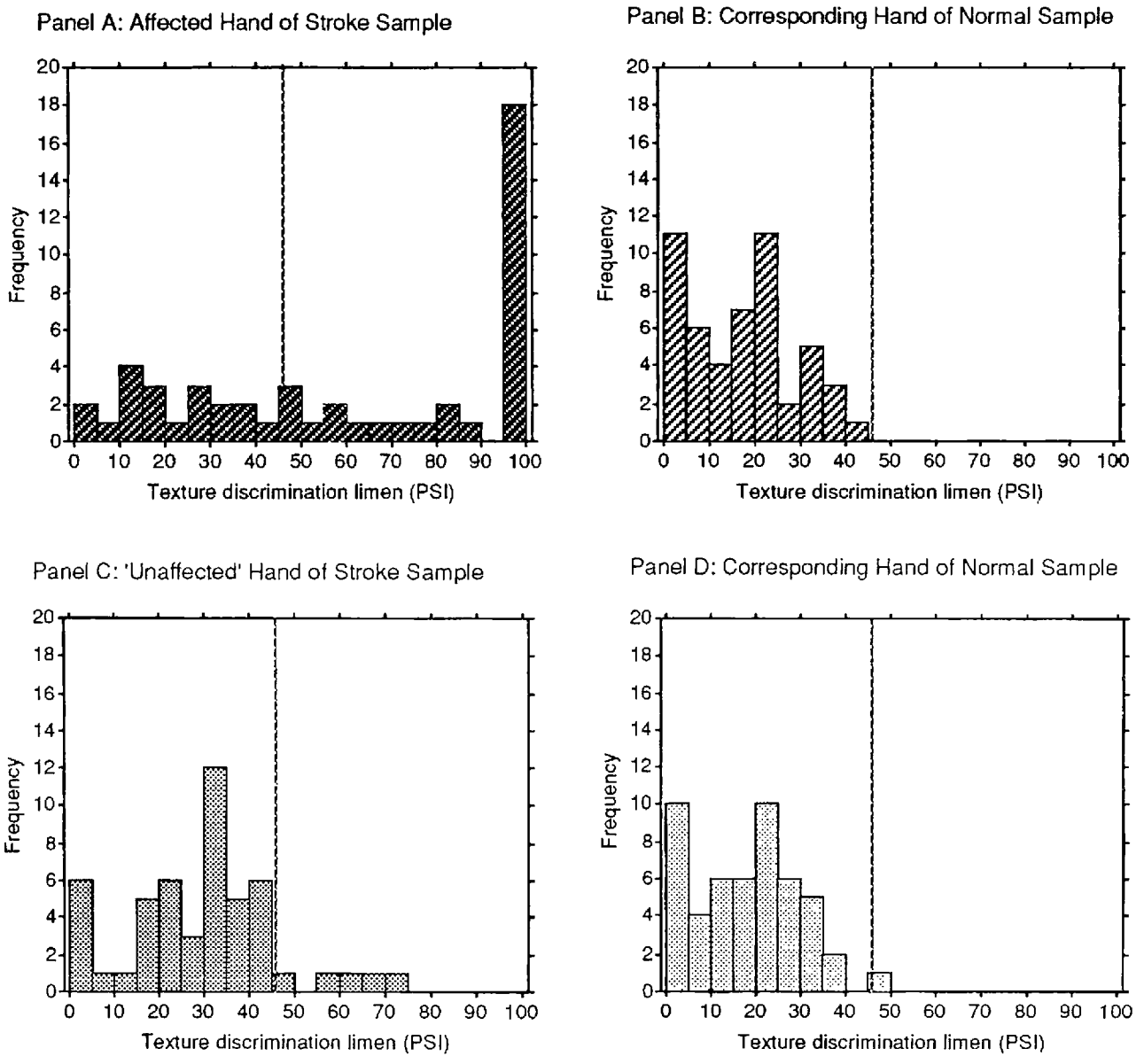

Figure 5. Frequency distribution of texture discrimination limens for affected and "unaffected" hands of stroke sample and corresponding hands of neurologically unimpaired sample.

and the forced-choice design. The discrimination function obtained in psychophysical studies with unimpaired subjects was typical of the classical psychometric function (50). Also, the defined spatial feature of the texture gratings has demonstrated a unique representation within the discharge patterns of the activated population of cutaneous mechanoreceptive fibers in the monkey's finger pad, implicating this feature as one that is coded in the somatosensory system (47). As Sathian and Zangaladze (71) state, "gratings . . . are members of a class of stimuli whose use in correlated psychophysical and neurophysiologic studies have greatly enhanced our understanding of the neural basis of tactile perception (p. 1464)." Influence of potentially confounding factors such as memory, comprehension, movement control, and fatigue are minimized by design features including repeated exploration, step by step instruction and demonstration, guided movement, frequent rests, and stratified presentation of surfaces. The stimuli are objectively defined, graded, allow small scale changes and the physical dimensions

of the surfaces range from the smallest differences that can be discriminated by unimpaired subjects (50) to the largest ridged surface that might still be perceived as a rough surface (64). Although testing typically takes 15 to 20 minutes, this degree of sampling is required to adequately assess an individual's tactile perception across the range of surfaces. Further test development that includes using the device as a screening tool and reducing test time is currently being conducted.

The temporal stability of the measure was indicated by high test-retest reliability coefficients. Reliability scores were within recommended ranges (68,72), while still achieving high resolution. More important, error of measurement appears adequate for clinical monitoring. The SEM in estimating an individual score, 9 PSI, is substantially less than the often severe impairments observed (i.e., 100 PSI) and represents only 9 percent of the total TDT scale. In addition, the SEM for estimating a *change* from one session to another was 13 PSI, which is sufficiently small to clearly detect changes in a large proportion of patients. For example, to evaluate an individual's progress in tactile discrimination (when tested by the same therapist over time), the magnitude of change required to conclude an improvement in discrimination ability from test one to test two (with 95 percent confidence) would be a reduction in the discrimination limen of 30 PSI or more. Intervention studies conducted indicate a scope for improvements of the order of 30–90 PSI (59), suggesting that the measure is sufficiently reliable for clinical monitoring. The stability of the measures has also been demonstrated under repeated test conditions (over 10 to 20 test sessions) in the baseline data of interrupted time series experiments (59).

High reliability coefficients obtained for the TDT ($r = 0.92$) compare favourably with reliability estimates for other measures of tactile ability tested at the hand with stroke patients (51). For example, Lincoln and co-workers (51) reported retest reliability values ranging from −0.21, for two-point discrimination at the palm, to 0.83, for detection of light touch at the hand. Reliability values for two-point discrimination at the fingertip and tactile localization at the hand were also relatively low, i.e., 0.57 and 0.40, respectively, whereas the value for stereognosis was higher, 0.74. These values obtained by Lincoln and associates (51) are based on a low-resolution, three-point categorical scale of clinical measurement. In comparison, the TDT provides a continuous scale yet still achieved high reliability estimates. In addition, the method of testing sensation investigated by Lincoln and associates (51) was more detailed and standardized than most clinical testing of sensation, suggesting that the reliability of the conventional sensory examination may be even poorer (52). Although Lincoln and associates (51) found relatively good consistency over time on some items when tested by the same therapist, the reliability between assessors was poor for most items, as has also been found in other studies with stroke patients (53–55).

Potential differences in reliability of higher and lower scores were revealed for the TDT. The error of measurement associated with the 100 PSI ceiling level was extremely low, reinforcing the certainty with which detection of an inability to discriminate textures can be made. However, lower in the scale the error of measurement was greater (11.4 PSI). Even allowing for this slightly larger estimate (cf. 9 PSI), the error is adequate for identification of impairment and detection of changes of clinically significant magnitude. Although there may be some reservation required for identification of marginal degrees of impairment, moderate to severe levels of abnormality would be confidently identified and monitored over time. If more precise measurement is required, marked reductions in error scores can be achieved with repeated testing, as demonstrated in Table 1. Averaging test scores may be particularly useful when scores around the criterion of abnormality are obtained. It should also be noted that one limitation imposed by the threshold approach is the natural ceiling effect in subjects who have severe impairment. This has led to a recent modification of the TDT which involves a stimulus matching procedure and matching sets of the plastic surface grids (2,73). The modified procedure reduces testing time, simplifies scoring, and provides better resolution when subjects have severe impairment (2,73).

Performance scores did not appear to be systematically influenced by level of familiarity with the tests or amount of practice on them. Although a significant difference was demonstrated between actual and expected slope and intercept values between sessions 1 and 2, the nature of this change was not consistent with a practice effect on the test. Some subjects who had a low discrimination limen on session 1 showed a higher limen (ie. poorer performance) at session 2. This effect may be partly due to the increased probability of scores near zero to shift above rather than below zero, given truncation of the scale at zero and a tendency for regression of data to the mean (68). In addition, as there is a natural ceiling effect at 100 PSI, it is not possible to determine if there is a similar trend at this end of the scale. Despite this mathematical explanation, it is important to note that the variable scores at the lower end of the scale were contained within the range of normal performance (up to 46 PSI, as reported in the normative study). Furthermore, scores did not continue to systematically vary in this way between sessions 2 and 3. Although it appears that scores with low discrimination limens are most likely to vary in session 1, these scores are within normal val-

ues and may not require retesting. If retesting is required, it would be preferable to repeat the initial test to provide a more stable estimate of performance at that point in time.

The TDT's demonstrated ability to identify impaired performance relative to normal standards supports its discriminative validity. The affected hands of stroke subjects demonstrated more frequent and severe impairment than the "unaffected" hands, as expected from the typical stroke syndrome (4). In addition, impairment in the "unaffected" hand is consistent with findings that sensory disturbances often occur bilaterally (3,57). Psychophysical and neurophysiologic investigations (47,50) related to the stimuli and methods of testing employed in the TDT also provided theoretical support for the tests being valid measures of tactile discrimination ability. Thus these factors provide converging support for the conclusion that the TDT can validly differentiate impaired tactile discrimination performance following stroke.

Objectively defined guidelines for interpretation were also provided by the normative study. This is particularly important given the potential for impairment in the "unaffected" limb (3,57) and the common clinical practice of using this limb as a point of reference. A conservative criterion of abnormality, that included all scores from the normal sample, was found at 46 PSI. In addition, a zone of uncertainty around the abnormality criterion was established at 31–61 PSI. Although the zone of uncertainty spans 30 PSI, impaired scores were clearly identified above the ranges indicated and unimpaired performance below these ranges. If an observed score is within the zone of uncertainty, strategies such as averaging test sores could be readily implemented by the clinician to facilitate more confident decision making.

Competing explanations for the test performance of stroke subjects do not appear plausible. Motor and memory impairments were unlikely to influence scores as normal limens were evident in some stroke subjects (despite varying degrees of paralysis), movements were guided in a standard manner and memory demands were minimized by the test design (1). Subject selection criteria eliminated the potential influence of neglect and inadequate comprehension. All but four stroke subjects with impaired scores in the affected hand concomitantly demonstrated scores within the normal range for the "unaffected" hand, which reduces the plausibility of impairment of attention and cognition as explanations for the impaired scores of the affected hand.

The obtained reliability and normative-discriminative findings appear generalizable to the wider population of stroke patients. Stroke subjects in the reliability study had tactile discrimination abilities representative of the full range. The low density of scores noted at 75–95 PSI was consistent with larger patient groups (as in the normative-discriminative study) suggesting that the sample employed was representative. Substantial change in discrimination ability would not be expected within the test-retest time interval sampled and subjects were tested after the initial 2-week period of most rapid recovery (74). Testing was conducted under standardized conditions, an equal number of subjects were tested with their affected versus "unaffected" hand first and a similar number of subjects did (16 subjects) or did not (19 subjects) require guided movement. The stroke sample for the discriminative study were sequentially selected from three major rehabilitation hospitals, providing a representative sample of the subpopulation of patients that present for rehabilitation. The age range was comparable to that of the adult stroke population, particularly those presenting for rehabilitation (75). Although more males than females were included, this was consistent with reported higher incidence of males (75).

Age was not significantly associated with touch discrimination threshold in the normal sample. This finding suggested that it was appropriate to combine the normative data across ages (i.e., 23 to 77 years) when interpreting performance scores. The finding is, however, at variance with most studies in this field. A decline in tactile sensitivity and spatial acuity of touch has been repeatedly demonstrated with advancing age (58,76–78). For example, Stevens (76) found that elderly subjects (66–91 years) had higher 2-point discrimination thresholds than young (18–33) or middle aged (41–63 years) subjects. These studies involved static touch perception using monofilaments (77), a probe (58), two-point aesthesiometer (76,78), or gap detection stimuli (78). In comparison, the TDT required dynamic touch discrimination of texture gratings. These differences in the nature of the somatosensory ability tested may have contributed to the contrary results. This explanation is supported by recent findings from Jeng and Radwin (36), who did not find a significant age effect for a dynamic test of gap detection, despite the presence of a small but significant effect when the test was performed statistically. It should be noted, however, that the normative study of Jeng and Radwin (36) comprised only a small sample ($n = 16$) with an age range from 21 to 66 years, which may also have contributed to the lack of a significant effect. Similarly, in the present study the relatively small sample size and observations that decline in tactile sensitivity is not universal (58) may have contributed to the findings. Thus, we should not discount the potential importance of age on dynamic touch discrimination until more extensive studies are undertaken.

In summary, the development of a quantitative, standardized measure of touch discrimination that can

be employed in clinical settings with stroke patients appears to provide an advance on current clinical measurement of brain damaged patients. The quantitative nature and strong empiric foundations of the TDT, coupled with the high prevalence of impaired tactile discrimination performance and inadequacy of existing clinical measures, indicate that the TDT should supplement or replace existing clinical measures. Clinicians can employ the TDT to quantify impairment and monitor the magnitude of change in performance more objectively. It is anticipated that this will be particularly valuable in rehabilitation settings where accurate information on the nature and severity of impairment is important in planning and evaluating treatment. Although it is recognized that the typical test time of 15 to 20 minutes per hand may be problematic, especially in some acute clinical settings, we are investigating shortened versions of the test to expand its clinical application. To ensure that the same phenomenon is being assessed and communicated across therapists, investigation of the interobserver reliability of the measure is also indicated (79). In the current study tactile discrimination ability of the preferred finger was investigated. The device may also be used to test other fingers or body parts. For example, gratings have recently been used to assess tactile spatial acuity at the lower lip and at each fingertip bilaterally (71). The authors found that acuity did not differ significantly between left and right sides or between digits one to four. There were significant differences between thresholds for the lip and fingertips and between the fifth and remaining digits. The test also seems applicable to a wide range of patients with neurologic impairment other than stroke, for example following peripheral nerve injury. This suggests a potential for broad clinical application when further reliability and normative studies have been conducted.

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