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A gap detection tactility test for sensory deficits associated with carpal tunnel syndrome

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An automated gap detection tactility test was investigated for quantifying sensory deficits associated with carpal tunnel syndrome (CTS). The test, which involved sensing a tiny gap in an otherwise smooth surface by probing with the finger, had functional resemblance to many work-related tactile activities such as detecting scratches or surface defects. Gap detection thresholds were measured using the converging staircase method of limits paradigm. Sixteen normal subjects between 21 and 66 years of age were tested for studying important factors affecting gap detection thresholds. Actively probing with the index finger had a threshold almost an order of magnitude more sensitive (mean = 0·19 mm, SD = 0·11 mm) than passive touch (mean = 1·63 mm, SD = 0·62 mm), which was similar to two-point discrimination. Average thresholds decreased by 24% as contact force increased from 25 to 75 g. Performance in this tactility test quickly stabilized and showed little learning effects over the period of the test, as evidenced by the lack of significant differences between six replicates. The results were highly repeatable. No significant threshold differences were observed between test and retest trials on different days, or between dominant and non-dominant hands. A contact force of 50 g was recommended as optimal for this test since it required moderate force but resulted in a smaller threshold compared with 25 or 75 g. A companion study was conducted using eight normal subjects and ten subjects diagnosed as having CTS. Average gap detection threshold, when finger probing was allowed, was 0·20 mm (SD = 0·11 min) for the normal subjects and increased two-fold to 0·40 mm (SD = 0·19 mm) for the CTS subjects. Average gap detection threshold, when the finger probing was not allowed, was 1·71 mm (SD = 0·53 mm) for the normal subjects and increased by 48% to 2·53 mm (SD = 0·87 mm) for the CTS subjects. The results suggest that people suffering from CTS may experience similar functional deficits in daily living and work activities. The small inter-subject variability makes this test a candidate for having utility as a monitoring test for loss of cutaneous tactile sensitivity.

1. Introduction

Quantitative, non-invasive instruments are needed for routinely assessing symptoms of peripheral neuropathies, such as carpal tunnel syndrome (CTS). Sensory symptoms represent the earliest and major deficit in most CTS cases. Kendall (1960) reported sensory changes in 86% and motor weakness 40% of the CTS patients studied. Inglis *et al.* (1972) found that 64% of the CTS patients complained of numbness, 30% of paraesthesiae, 46% of pain, and 3% of weakness in the hands. Although electrophysiological testing has been considered to be the definitive test for CTS, these tests do not measure symptoms or functional deficits. Furthermore, patients reporting sensory

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symptoms of median nerve compression may show little or not measurable sensory or nerve conduction changes (Grundberg 1983, Spinner *et al.* 1989).

Two-point discrimination tests have long been used for assessing tactile sensory impairment (Dellon *et al.* 1987, Moberg 1990). This test has been shown to be reliable for measuring functional nerve regeneration, but is not sensitive to the gradual decrease in nerve function created by external compression (Lundborg *et al.* 1982). Alternative sensory testing techniques, such as monofilaments, lack the control of important variables (Levin *et al.* 1978), are time consuming, expensive, not readily available, and results may be dependent on examiner experience and training (Bell-Krotoski *et al.* 1993). A particular concern for sensory evaluation is the mechanical characteristics of the stimuli being delivered, which affect the thresholds obtained. These are usually under manual control of the examiner, and so the rate of impact and the extent of skin deformation can vary from one trial to the next (Bell-Krotoski and Buford 1988, Bell-Krotoski *et al.* 1993, Dellon *et al.* 1987, Moberg 1990).

Common tactile sensation involves not only passively receiving and processing information from skin deformations, but also active exploration of surfaces and features. Few studies have investigated finger tactile thresholds while allowing natural, active exploration of a surface owing to the difficulty in producing accurate and high resolution stimuli. Radwin *et al.* (1993) developed a computer-controlled aesthesiometer that was capable of measuring tactile sensitivity thresholds using freely active finger probing. What distinguished this test from conventional tactility tests is that it measured performance in a functional tactility task resembling those performed during common work activities. Although test conditions were highly controlled, this test still permitted natural finger probing activity while measuring ability for sensing surface feature defects like scratches, rather than sensing static unnatural sensory stimuli such as distinguishing two points, or detecting a point-pressure stimulus.

This study reports gap detection thresholds for sixteen healthy working age subjects using the new aesthesiometer. The purpose of the investigation was to determine population normative responses, study reliability of this test as a routine monitoring tool, investigate important factors that affect the sensory threshold, and determine optimal test conditions for administering the test. After the normative data were obtained, a comparison study using eight control subjects and ten patients diagnosed as having CTS was conducted to determine if the gap detection test can measure sensory deficits associated with CTS.

2. Pilot study

A pilot study was conducted to investigate the feasibility of this test by milling a flat polished surface on top of the jaws of a precision vice and using steel shims to produce a gap. The contact force was controlled using a simple lever system with a counterbalance weight so that finger contact force was set to 70 g. Four subjects aged between 20 and 29 years were tested. The test used the method of constant stimuli in order to determine gap detection thresholds. Ten standard spaces (Craftsman 40804) were used for setting the gap width. They were 0·05, 0·10, 0·15 0·20 0·25, 0·31, 0·41 0·51, 0·61 and 0·71 mm. Every subject was tested four times for each gap size. The stimulus presentation order was randomized for each subject.

Subjects were instructed how to feel the gap using the index finger while viewing the stimulus platform before actually starting to collect data. During the experiment, however, subjects were told to look away in order to avoid response bias from visual cues. After setting the gap size according to the randomized stimulus order, the

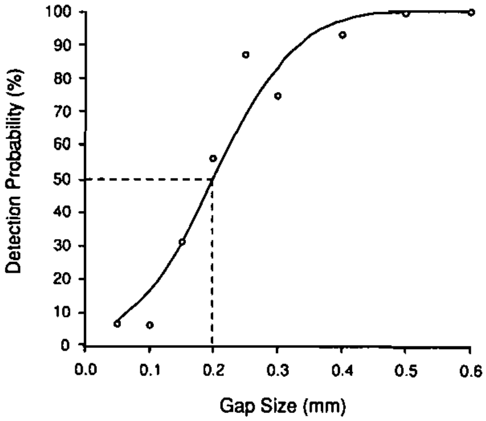

Figure 1. Index finger tactile thresholds cumulative normal response curve for four normal subjects. Each point represents the mean response probability for all subjects. The dashed line indicates the 50% gap detection threshold.

experimenter assisted subjects in positioning the finger on the stimulus. Subjects were instructed to apply enough force against the platform in order to make the tilted level balance. The required force was 70 g, measured using a gram gauge (Halda, 5–150 g). Subjects probed the stimulus while keeping the level horizontal. Multiple strokes were allowed before subjects reported if they could feel the gap. Subjects were provided with a short break after they responded for the experimenter to set the gap width to the next trial. Only the right hand was tested. It took 45 min to measure a threshold for each subject.

Gap detection thresholds were estimated using probit analysis for each subject, as well as for the aggregate group responses. The average gap detection threshold for the four subjects was 0·20 mm (SD = 0·03 mm). Using four responses for four subjects at each gap width, a cumulative normal probability plot was constructed (figure 1).

Since the stimulus platform surface for the pilot test had some unavoidable misalignment, a slight height difference was detected between the two sides of the vice when the jaws were completely closed. This misalignment was not observed when the vice jaws were not in direct contact. The pilot experiment therefore did not include the closed vice as a zero gap stimulus. A small intercept for the fitted cumulative normal function occurred because one of the sixteen responses was 'yes' for the smallest gap width which was 0·05 mm. Based on success with the pilot study a new automated and more precise apparatus was developed (Radwin *et al.* 1993).

3. Experiment 1: Normative performance and reliability study

3.1. *Methods*

An experiment was conducted for investigating factors that might affect gap detection sensory thresholds and for obtaining normative performance data using subjects free of hand disorders.

3.1.1. *Test apparatus and paradigm*: A computer-controlled aesthesiometer based on the pilot apparatus was constructed and used for measuring finger tactile sensitivity. Construction details are provided in Radwin *et al.* (1993). The gap stimulus was produced by separating two highly polished adjacent blocks using a precision

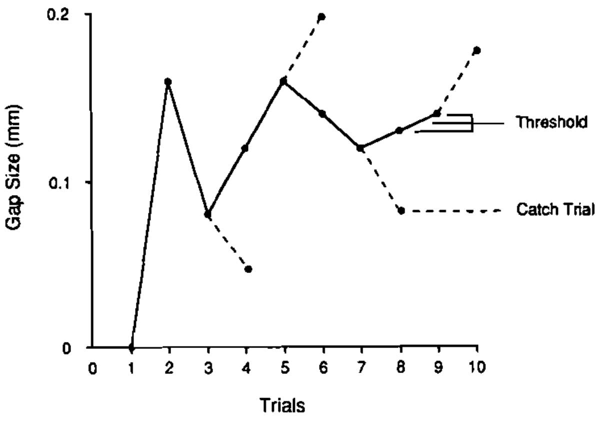

Figure 2. A representative response set for the converging staircase paradigm and corresponding gap widths. Sensory threshold is the average gap width of the last two responses. Dotted lines represent possible catch trials that are randomly inserted.

micrometer motor (Oriel Encoder Mike™ 18212). Signals for micrometer displacement, speed and direction were communicated to an i286 microcomputer using a MetraByte DAS-16 digital-analog converter (DAC) and digital I/O (DIO) data acquisition board. Finger contact force variance was controlled to less than 1·0 g by using a precision balance beam system.

Static as well as dynamic sensory functional tests were possible using this aesthesiometer. The dynamic test measured tactile sensory threshold while actively probing the stimulus surface for a gap. A subject freely probed the platform surface using the finger tip while applying a constant force against the stimulus platform. A finger support was used when testing tactility for a static sense. The support exposed the distal phalangeal pad while preventing the finger from exerting any force perpendicular to the stimulus platform and from moving the finger across the platform. The platform was then positioned against the stationary finger. Visual cues were eliminated by enclosing the apparatus and providing an aperture for the finger.

Since time for conducting the test was important, the method of constant stimuli used in the pilot study was not considered to be practical. A converging staircase method, which was variation of the method of limits, was therefore used for determining gap detection sensory thresholds. Gap detection thresholds were estimated by convergence while titrating about the threshold using smaller and smaller discrete steps in gap size (figure 2). Five gap step-size decrements were used. Each gap size was half the magnitude of the previous one. Change in gap step-size and direction occurred every time a response was different from the previous one. The initial step size was 0·16 mm for the dynamic test, and 1·6 mm for the static test. A threshold determination took less than 5 min using this method.

A catch trial was randomly inserted after successive responses were different (figure 2). When this occurred, instead of changing the gap size in the opposite direction, the gap was made even smaller for a descending series or larger for an ascending series. An error subsequently occurred if subjects reported that they felt a smaller gap but not a larger gap for an ascending series, or when they reported that they could not feel a larger gap but could feel a smaller gap in a descending series. When an error occurred the gap was reset to the gap size two steps before the catch trial, or the experimenter requested the subject to repeat the trial. The frequency of errors was less than 5% for all subjects in all trials.

3.1.2. *Subjects*: Sixteen adult subjects participated in the normative performance and reliability study. Subjects were recruited by posting announcements on bulletin boards around the university campus. Nine males and seven females ranging between 21 and 66 years of age participated in this experiment. Fourteen of the sixteen subjects described themselves as right-handed. Since age was considered to be an important factor in tactile sensitivity, the subjects recruited for this study covered a wide age range representing the adult working population. Four subjects were recruited for each of the four age categories, (1) <25 years, (2) 25–40 years, (3) 40–55 years, and (4) 55–70 years old. Subjects were paid for participating in this study and received an extra bonus if they completed the entire experiment.

Before participating, all subjects were provided with a questionnaire requesting some basic information including name, gender, occupation, age, and handedness. The questionnaire also queried if subjects previously had any musculoskeletal disorders, diseases, or hand injuries including diabetes, arthritis, carpal tunnel syndrome, tendinitis/synovitis, Raynaud's syndrome, nerve injuries, or fractures. Carpal tunnel syndrome symptoms such as numbness, tingling, pain, and weakness were also included in the questionnaire. Subjects were not recruited if they responded affirmative to any of the above symptoms, disorders, or diseases.

3.1.3. *Experimental design*: An experiment was conducted for determining the effects of learning and fatigue, intra-subject differences between two hands, dynamic and static touch, contact force, inter-subject variability, and test-retest reliability for a normal subject population performing a gap detection threshold task. The experimental design is summarized in figure 3. The order of experimental conditions was counterbalanced between all subjects.

The experiment was conducted in two sessions on two different days. Six replicates for each dynamic and static condition were presented during the first session for studying the effects of learning and fatigue. Subjects used only the dominant hand and

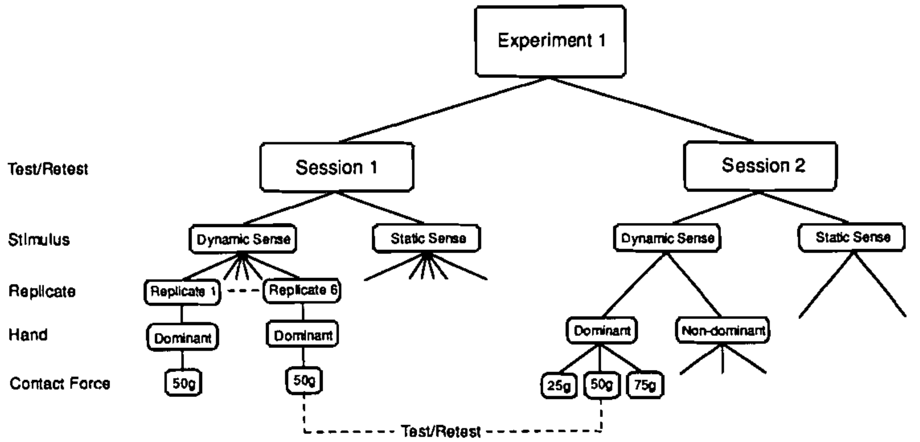

Figure 3. Factorial experimental design for the normative performance and reliability gap detection sensory threshold study (experiment 1).

contact force was fixed at 50 g for the first session. Subjects were required to return on the same day and time, one week following initial testing. The second session studied the effects of dominant and non-dominant hands, dynamic and static touch, and contact force. There were no replicates in the second session.

A repeated measures analysis of variance (ANOVA) was performed using data collected in the first session for studying the effects of dynamic and static sense, replicates, and their interactions. Age was treated as a covariate for this analysis. Tukey studentized range tests were also performed for comparing the six replicates. The day for the dominant hand using a contact force of 50 g for each dynamic and static touch condition in the second session was compared with the sixth replicate of the same condition from the first session in order to study test/retest availability. Threshold differences between the first and second sessions were tested using a simple one-way ANOVA with age as a covariate, and the Pearson product correlation coefficient between the two sessions. The effects of hand dominance, contact forces, and their interactions were also studied using ANOVA with age as a covariate.

3.1.4. *Experimental procedures*: Subjects were first familiarized with the test by viewing the gap in the stimulus platform. The experimenter then asked subjects to probe the gap using the index finger starting with the gap set to zero. Subjects were provided with practice trials including gap widths that they can detect easily and those that they cannot detect at all.

A trial began by first resetting the stimulus stage to zero for calibrating the system. The gap was randomly set to initial settings of zero or to a gap size of 1·6 mm or 0·16 mm, depending on whether the test was static or dynamic, respectively. A dynamic tactility trial started after an auditory warning was sounded, signalling subjects to insert the index finger inside the aperture and begin probing the stimulus platform. Subjects then received an auditory prompt every 3 s until they verbally responded if they could, or could not detect a gap. The examiner entered the subject's response using the computer keyboard. The finger was then withdrawn after responding. A 3 s rest period was provided, while the gap was changed in size before the next trial began.

The finger was held in a fixed position using a finger support for the static tactility test. An auditory warning was sounded 2·5 s before the stimulus platform automatically contacted the finger. A prompt signal was sounded every 3 s after the stimulus made contact until the subject verbally responded if they could or could not detect the gap. When the examiner keyed in the response the stimulus stage was automatically lifted off the finger.

3.2. *Results*

Average dynamic tactile sensitivity thresholds for the index finger (mean = 0·19 mm, SD = 0·11 mm) were almost an order of magnitude less than for static tactile thresholds (mean = 1·63 mm, SD = 0·62 mm) ($F(1, 15) = 164{\cdot}04, p < 0{\cdot}001$). Average thresholds for the sixteen normal subjects ranged between 0·05 mm to 0·45 mm for the dynamic sensory test, and 0·70 mm to 3·15 for the static sensory test. The Pearson product correlation coefficient between all dynamic and static thresholds was 0·77 ($p < 0{\cdot}001$).

No significant threshold differences were observed between the means of six replicates for the dynamic and static sensory tests ($F(5, 75) = 0{\cdot}48, p > 0{\cdot}5$). There were no significant interactions observed between stimulus × replicate ($F(5, 75) = 0{\cdot}40$, $p > 0{\cdot}5$). No significant threshold differences were observed between thresholds recorded for the test and retest sessions ($F(1, 15) = 0{\cdot}02, p > 0{\cdot}5$). Average thresholds

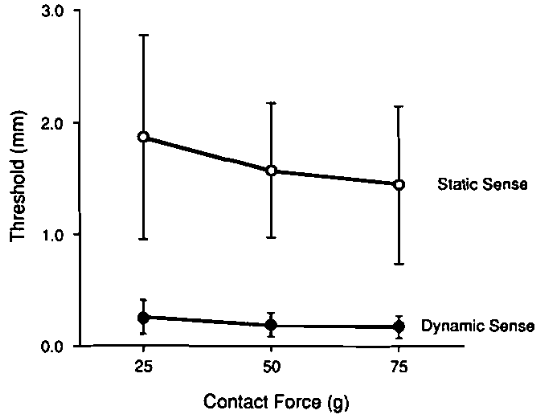

Figure 4. Mean gap detection sensory thresholds for 16 normal subjects plotted against contact force.

between test and retest had a correlation coefficient of 0·94 ($p < 0{\cdot}001$). The correlation coefficient for thresholds between test and retest sessions was 0·75 for the dynamic sensory test ($p < 0{\cdot}001$) and 0·93 for the static sensory test ($p < 0{\cdot}001$).

Thresholds decreased as contact force increased from 25 to 75 g for both the dynamic and static tests ($F(2, 30) = 17{\cdot}73, p < 0{\cdot}001$) (figure 4). The Tukey studentized range test indicated that both dynamic and static tactile sensitivity thresholds for a 25 g contact force were greater than for 50 or 75 g ($p < 0{\cdot}01$). No significant threshold differences for either the dynamic or the static tests were observed between 50 and 75 g using the Tukey test ($p > 0{\cdot}05$). The interaction between stimulus × force was statistically significant ($F(2, 30) = 6{\cdot}87$, $p < 0{\cdot}01$) (figure 4). Thresholds for the dynamic sensory test decreased by 28% as contact force increased from 25 to 50 g. Thresholds for the static sensory test decreased by 16% as contact force increased from 25 to 50 g. Dynamic sensory thresholds also had less variability among subjects as evidenced by the smaller standard deviations (figure 4). There was no significant overall hand effect ($F(1, 15) = 1{\cdot}81$, $p > 0{\cdot}1$) or interaction between hand and stimulus ($F(1, 15) = 1{\cdot}50, p > 0{\cdot}1$). Therefore the dynamic or static sensory thresholds between dominant hands and non-dominant hands were not significantly different.

4. Experiment 2: Comparison between normal and CTS subjects

4.1. *Methods*

The objective for this experiment was to investigate whether the gap detection threshold test can measure sensory deficits associated with CTS. The subjects included both CTS patients and normal subjects. This experiment consisted of a repeated measures full factorial design using hand as random effects variable nested within a group, and using age as a covariate. All hands were treated as individual members in either the control or the CTS group.

4.1.1. *Subjects*: Ten out-patients diagnosed as having CTS volunteered for the study. Eight patients had bilateral CTS and two patients had unilateral CTS, providing 18 CTS hands. All the CTS patients were female and right-handed, ranging in age between 27 and 76 years. The mean age for the CTS group was 42·3 years. Eight asymptomatic control subjects were also recruited from the university community by posting advertisements. There were five females and three males, ranging in age between 30 and 52 years in the control subject group. Six of the eight control subjects described themselves as right-handed and two subjects were left-handed. The mean age for the normal group was 41·9 years. All subjects (normal and CTS) were examined by physician and were administered a nerve conduction study.

Criteria for accepting CTS subjects included CTS symptoms based on case history and physical examination, and electrodiagnostic parameters compatible with a lesion of the median nerve in the carpal tunnel. Symptoms included paresthesia, numbness, or pain in the sensory areas of the distribution of the median nerve in the hand occurring at night or during daily activity. Physical examination findings included hypesthesia in the median nerve sensory distribution of the hand or weakness in the muscles innervated by the median nerve. Phalen's test was included in the physical examination for CTS patients. A positive Phalen's sign was a necessary condition for CTS. In all cases no evidence of history or physical examination was suggestive of another neurologic disorder such as peripheral neuropathy, cervical radiculapathy or other nerve entrapments.

4.1.2. *Experimental design*: A mixed-model repeated measures ANOVA was performed for the comparison between normal and CTS subjects. Factors included group (CTS and control subjects), stimulus (dynamic and static), and contact force (25 and 50 g). CTS subjects were tested for both hands even though some of them had only one symptomatic hand. Unilateral CTS subjects' asymptomatic hands, however, were not regarded as normal and therefore were not pooled with the control group. Data from the asymptomatic hands were not included in the analyses of the current study. Each subject was tested for all conditions of hands, contact forces and stimulus. The presentation order was counterbalanced between subjects in each group.

4.2. *Results*

The analysis of variance results for the gap detection test among CTS and control subjects indicated that subject population, contact force, and stimulus (static and dynamic) all significantly affected the gap sensory threshold. The average dynamic gap detection threshold was 0·20 mm (SD = 0·11 mm) for the normal subjects, and doubled to 0·40 mm (SD = 0·19 mm) for the CTS subjects ($F(1, 31) = 13{\cdot}64$, $p < 0{\cdot}001$). The average static sensory threshold was 1·71 mm (SD = 0·53 mm) for normal subjects and increased by 48% to 2·53 mm (SD = 0·87 mm) for the CTS subjects ($F(1, 31) = 13{\cdot}41$, $p < 0{\cdot}001$) (figure 5).

As contact force increased from 25 to 50 g, the dynamic sensory threshold decreased from 0·34 mm (SD = 0·19 mm) to 0·26 mm (SD = 0·19 mm) for all hands ($F(1, 33) = 39{\cdot}76$, $p < 0{\cdot}001$). The static sensory threshold decreased from 2·32 mm (SD = 1·06 mm) to 1·95 mm (SD = 0·65 mm) for all hands as contact force increased from 25 to 50 g ($F(1, 33) = 10{\cdot}44$, $p < 0{\cdot}01$). Overall average static sensory thresholds (mean = 2·13 mm, SD = 0·81 mm) were seven times greater than dynamic sensory thresholds (mean = 0·30 mm, SD = 0·18 mm) for all hands ($F(1, 32) = 281{\cdot}19$, $p < 0{\cdot}001$).

Average gap detection thresholds for the static and dynamic tests are plotted against age in figure 6. Linear regression using average threshold as the dependent variable and age as an independent variable indicated that the effect of age significantly contributed to the variance in the static sense test for both the CTS group)$F(1, 16) = 5{\cdot}35, p < 0{\cdot}05$) and the normal group ($F(1, 14) = 6{\cdot}11, p < 0{\cdot}05$). The effect of age did not significantly

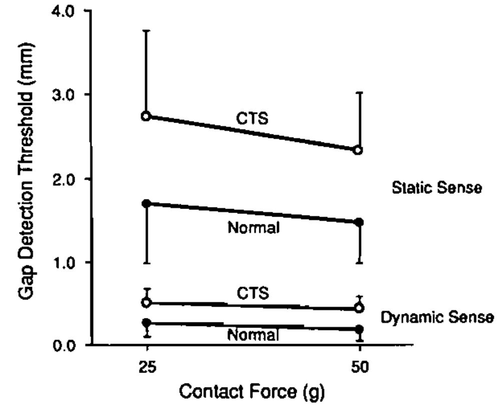

Figure 5. Mean gap detection sensory thresholds for 18 CTS hands and 16 normal hands plotted against contact force.

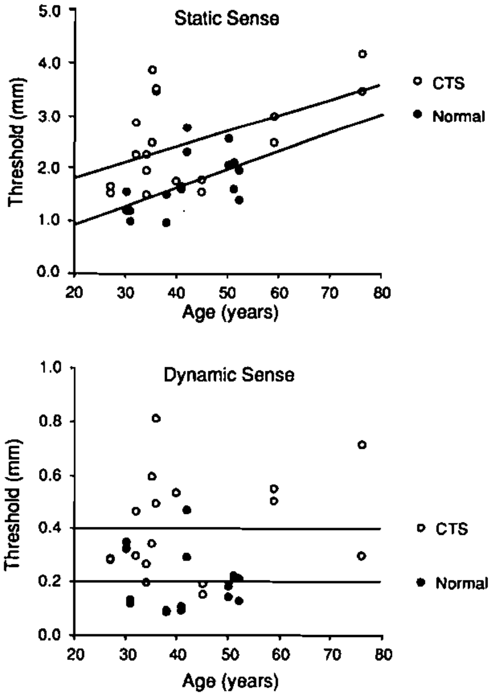

Figure 6. Index finger static and dynamic tactile thresholds for normal and CTS hands plotted against age. Note that the ordinate for the static sense and dynamic tactile conditions are different scales. Regression model for the CTS group for static sense was threshold (mm) = 1·31 + 0·029 × Age ($r^2 = 0{\cdot}25$). Regression model for the normal group for static sense was threshold (mm) = 0·26 + 0·035 × Age ($r^2 = 0{\cdot}30$).

contribute to the variance in the dynamic sense test for either the CTS group ($F(1, 16) = 1\cdot40$, $p > 0\cdot1$) or the normal group ($F(1, 14) = 0\cdot15$, $p > 0\cdot5$).

5. Discussion

A routine test should be capable of being administered in a practical amount of time. It took 45 min to measure a threshold using the method of constant stimuli but only 5 min using the convergent staircase technique, a variant of method of limits. The average normal threshold for the four pilot subjects (mean = 0·20 mm, SD = 0·03 mm) was very close to the average threshold measured for the 16 normal subjects using the staircase method for a contact force of 75 g. The latter had a mean threshold of 0·19 mm (SD = 0·11 mm). A t-test comparing these two means showed no significant difference between then ($t(18) = 0\cdot477, p > 0\cdot5$). Similar average thresholds for these two methods indicated that the staircase method determined a threshold more rapidly but without introducing more response bias than the method of constant stimuli. The method of constant stimuli or the staircase method, however, does not prevent subject response biases (Kantowitz and Roediger 1984). Bove *et al.* (1986) recommended use of the two alternative, forced choice procedures to minimize variability in decision criteria present using the method of limits. Gerr and Letz (1988) demonstrated that the method of limits procedure was more reliable and less time-consuming than the forced choice procedure for cutaneous vibration thresholds, and thus more suitable for clinical testing. For the time constraints inherent in using the gap detection test in the field, the staircase method was an efficient and reliable testing paradigm.

Thresholds decreased as contact force increased from 25 to 75 g for both dynamic and static sensory tests. Thresholds were different between 25 and 50 g contact forces for both dynamic and static sensory tests, but were not different between 50 and 75 g (figure 4). Therefore a contact force of 50 g was recommended as the optimal force condition for this test since it required moderate force but resulted in a low threshold, compared to 25 or 75 g. The results suggested that the relationship between contact force and tactile sensitivity was not a simple linear function.

The effect of force applied to the skin and depths of skin indentation on tactile sense was studied by Mountcastle *et al.* (1966) and Kenshalo (1978). Skin indentation depth was thought to be a good predictor of tactile sensation intensity. As contact pressure increases, the skin indents more. The relationship between skin indentation depth and contact force has been shown not to be a linear function (Petit and Galifret 1978). Since skin indentation rate decreases as contact pressure increases, this could explain the finding that increasing contact force from 50 to 75 g did not decrease tactile thresholds significantly.

Lederman and colleagues undertook a series of experiments studying the perception of suprathreshold tactile stimuli (Lederman and Taylor 1972, Lederman 1974, Lederman *et al.* 1982). The subjective response was perceived roughness of grooved surfaces. Groove width, as well as finger force, had significant effects on perception or roughness. The rate of stroking motion was not a significant factor for perceiving surface roughness. The current study used different tactile stimuli than the roughness studies; however, the results concluded that different contact forces affected tactile thresholds significantly. Although the rate of stroking was not controlled, it was not considered to be important.

The dynamic sensory test resulted in different responses than for the static sensory test when contact force changed, as evidenced by the significant interaction between contact force and stimulus type (figure 4). Thresholds for the dynamic sensory test decreased more as contact force was increased from 25 to 50 g, compared to the static sensory test. The results indicated that the dynamic sensory test was more sensitive than the static sensory test to changes in contact force between 25 and 50 g. Further increasing the contact force to 75 g did not result in lowering the thresholds for either dynamic or static sensory tests. Therefore the optimal test condition for the gap detection aesthesiometer would be conducting the dynamic sensory test for a contact force of 50 g.

The absence of significant threshold differences between six replicates indicated that the test paradigm used in this study required very little learning to reliably measure both dynamic and static sensory thresholds. This is a desirable feature of experimental and clinical tests since it does not take excessive training time to start to collect reliable data. It is not only desirable in terms of time savings, but also in terms of maintaining motivation and vigilance levels.

The subject age in the normative study (experiment 1) ranged from 21 years to 66 years. Age may be an essential factor when dealing with sensory function, it was necessary therefore to account for age effects on tactile sensitivity thresholds. The statistical model in the present study used age as a covariate. No significant age effects, however, were observed. Using 80 subjects between the ages of 18 and 91 years, Stevens (1992) found that elderly subjects (66–91 years) had higher two-point discrimination thresholds than young subjects (18–33 years) or middle-aged subjects (41–63 years). Tactile sensitivity differences were not observed between young subjects and middle-aged subjects, which is the age range of the working population. Woodward (1993) observed a similar age effect for two-point thresholds.

Thornbury and Mistretta (1981) found a small, but statistically significant, increase in threshold as age increased for Semmes-Weinstein pressure thresholds for the pad of the index finger. They also noticed that a number of subjects of over 60 years of age retained high tactile acuity. Fourteen subjects (about 25% of their sample) could detect the stimulus at the lowest possible intensity (1·65) for more than 50% of the trials. There were five subjects over 60 years among the fourteen subjects. Haines *et al.* (1988) did not observe any age effects when testing depth sense thresholds for 91 workers having a mean age of 41 years. A study by Radwin *et al.* (1991) observed no significant age effects when comparing ridge detection thresholds between sixteen normal subjects having an age range of from 25 to 67 years and nine carpal tunnel syndrome patients aged between 29 and 60 years. These inconsistencies suggest that the type of stimulus was an important factor. A small but significant age effect was observed in the current study for the static thresholds for both normal and CTS subjects (figure 6). However, there was no significant age effect observed for the dynamic test for both normal and CTS subjects. Since the static sense was similar to two-point discrimination, this was consistent with previous findings.

There was a significant age effect for the static sensory threshold. No age effect was observed for the dynamic sensory threshold. The wide distribution of the dynamic sensory threshold between the ages of 27 and 76 years (figure 6) suggests that increasing the sample size may not change the findings in the current study. Treating hands as individuals could possibly affect results to be significant, due to increasing the degrees of freedom, when in fact it is not significant. This is not the case for the dynamic sensory threshold in the current study.

Measuring tactile sensitivity for detecting an irregular shape on a smooth surface is a great challenge. Using contact photolithography to construct surfaces with raised dots, Johansson and LaMotte (1983) were able to demonstrate that people can detect a dot height of only 1 μm, when the dot diameter was larger than 600 μm, by stroking with the fingertip from an otherwise smooth surface. The study did not control the contact force when the fingertip was allowed to probe the surface. A servocontrol system was used in their subsequent studies to control skin indentation or contact pressure (LaMotte and Srinivasan 1987, LaMotte and Whitehouse 1986). The experiment paradigm, however, was designed so that the fingertip passively received a stimulus under machine control. The result from their study suggested that the lateral deformation of elevated regions of the skin activated rapid adapting (RA) mechanoreceptors. The responses of RAs alone accounted for the sensory capacity to detect a dot of minimal height on a smooth surface with the finger pad. The difference between the static and dynamic sense in the current study is the presence of lateral skin deformation for the dynamic sense.

The gap detection test used in this investigation was designed to measure performance in a task that resembled tactility tasks normally performed in daily occupational activities, such as tactile inspection for scratches or surface defects. Finger stroking and stimulus indentation are important factors in the stimulation and response of cutaneous mechanoreceptors (LaMotte and Srinivasan 1987). Performance in tests like two-point discrimination, or localized mechanical pressure detection (Semmes-Weinstein monofilament) does not directly correspond to functional deficits in tasks employing tactility, like inspecting for scratches, burrs, or surface roughness. Consequently it is difficult to relate changes in these measurements to human performance in common tactility tasks (Bell-Krotoski *et al.* 1993). The ability to quantify performance in these types of tasks could directly measure occupational deficits associated with peripheral neuropathies such as carpal tunnel syndrome.

The results of this study indicated that as a population, the CTS gap detection thresholds were greater than normal thresholds. It suggests that people suffering from CTS may experience similar functional deficits in daily living and work activities. Average gap detection dynamic sensory threshold was 0·25 mm and 0·24 mm higher for the CTS group than the normal group at contact force of 25 and 50 g respectively (figure 5). Radwin *et al.* (1991) observed a similar magnitude of tactile sensitivity shift for a group of 16 hands as having CTS. Using a ridge detection task, the CTS group had a 150% greater threshold than the normal group. Overall average ridge detection threshold was 0·08 mm for the normal subject sample and increased to 0·20 mm for the CTS subjects. The problem with the ridge detection test was that there was considerable variation within subjects. The average coefficient of variance was 78% for both the normal subjects and CTS subjects. The average coefficient of variance was 19% for the dynamic test and 18% for the static test in six replicates in experiment 1 of the gap detection experiment. The gap detection test had a high test-retest reliability, as evidenced by the high correlation coefficient of the test and retest sessions ($r = 0{\cdot}94$, $p < 0{\cdot}001$).

There were two CTS subjects having unilateral CTS. Those two subjects would have had to be eliminated in order to construct a complete block design or each hand had to be treated as an individual subject. Owing to the relatively small sample size, eliminating two unilateral CTS cases would have reduced the CTS data by 12%. Hand was therefore treated as an individual subject. The magnitude of the differences between the CTS and control subjects for the gap detection tests suggests that the results are robust despite the potential subject correlation bias.

To obtain the sensitivity and specificity of the dynamic sensory threshold and the static sensory threshold for CTS, 95% confidence interval was chosen as the upper normal boundary. A positive CTS case was defined as at least one positive test score from the 25 and 50 g conditions. The dynamic sensory threshold had a sensitivity of 0·44 and a specificity of 0·94 for differentiating CTS hands from normal hands. The static sensory threshold had a sensitivity of 0·44 and a specificity of 0·88 for differentiating CTS hands from normal hands. When a positive case was defined as at least one positive test score from the dynamic and static sensory thresholds, the test had a sensitivity of 0·61 and a specificity of 0·88. A test battery including the gap detection test and a rapid pinch and release psychomotor test had a sensitivity of 0·78 and a specificity of 0·81 for CTS (Jeng *et al.* 1994).

Although the average gap detection sensory thresholds between the two groups were significantly different, there appeared to be overlap between subjects in both groups. This overlap indicated that some members of the normal group have poorer performance in the gap detection task than some CTS subjects. Threshold differences between individual subjects in the normal group may represent the limits of normality. Individual differences between CTS subjects may have been owing to differences in the level of severity of the disorder. Further investigations are needed to study the relationship between the performance in the functional gap detection test and median nerve electrophysiological variables, such as sensory latencies or transcarpal latencies, in order to evaluate the efficacy of tests to detect CTS.

6. Conclusions

The results suggest that, on the average, workers suffering from CTS may not detect a surface with scratches in a tactile inspection task unless it is twice as large as detected by workers without CTS. The normative study indicated that the gap test was easily administered and determined tactile sensitivity rapidly. The gap test was learned quickly and test results had high repeatability. A contact force of 50 g was recommended as the optimal force condition since it required moderate force but resulted in a low threshold. The low inter-subject variability of the dynamic test will ensure a high sensitivity when it is used as a monitoring tool for detecting sensory deficits. Further investigations are needed for understanding the relationship between performance in the gap detection test and physiological evidence of nerve injuries before the test can be used as a monitoring tool.

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References

BELL-KROTOSKI, J. and BUFORD, W. 1988, The force/time relationship of clinically used sensory testing instruments, *Journal of Hand Therapy*, **1**, 76–85.

BELL-KROTOSKI, J., WEINSTEIN, S. and WEINSTEIN, C. 1993, Testing sensibility, including touch-pressure, two-point discrimination, point localization, and vibration, *Journal of Hand Therapy*, **6**, 114–123.

BOVE, F., LITWAK, M. S., AREZZO, J. C. and BAKER, E. L. 1986, Quantitative sensory testing in occupational medicine, *Seminars in Occupational Medicine*, **1**, 185–189.

DELLON, A. L., MACKINNON, S. E. and CROSBY, P. M. 1987, Reliability of two-point discrimination measurements, *Journal of Hand Surgery*, **12A**, 693–196.

GERR, F. E. and LETZ, R. 1988, Reliability of a widely used test of peripheral cutaneous vibration sensitivity and a comparison of two testing protocols, *British Journal of Industrial Medicine*, **45**, 635–639.

GRUNDBERG, A. B. 1983, Carpal tunnel decompression in spite of normal electromyography, *Journal of Hand Surgery*, **8**, 348–349.

HAINES, T., CHONG, J., VERALL, A. B., BERNHOLZ, C., SPEARS, R. and MUIR, D. C. F. 1988, Aesthesiometric threshold changes over the course of a work shift in miners exposed to hand-arm vibration, *British Journal of Industrial Medicine*, **45**, 106–111.

INGLIS, A. E., STRAUB, L. R. and WILLIAMS, C. S. 1972, Median nerve neuropathy at the wrist, *Clinical Orthopaedics and Related Research*, **83**, 48–54.

JENG, O.-J., RADWIN., R. G., HARMON, R. L. and LOTZ, B. P., 1994, Carpal tunnel syndrome psychomotor and sensory functional tests, *Proceedings of the 12th Triennial Congress of the International Ergonomics Association* (Human Factors Association, Canada), **3**, 240–243.

JOHANSSON, R. S. and LAMOTTE, R. H. 1983, Tactile detection thresholds for a single asperity on an otherwise smooth surface, *Somatosensory Research*, **1**, 21–31.

KANTOWITZ, B. H. and ROEDIGER, H. L. 1984, *Experimental Psychology*, 2nd edn (West, St Paul), 114–142.

KENDALL, D. 1960, Aetiology, diagnosis, and treatment of paraesthesiae in the hand, *British Medical Journal*, **2**, 1633–1640.

KENSHALO, D. R. 1978, Biophysics and psychophysics of feeling, in E. C. Careterette and M. P. Friedman (eds), *Handbook of Perception: Feeling and Hurting* (Academic Press, New York), VIB, 29–74.

LAMOTTE, R. H. and SRINIVASAN, M. A. 1987, Tactile discrimination of shape: responses of slowly adapting mechanoreceptive afferents to a step stroked across the monkey fingerpad, *Journal of Neuroscience*, **7**, 1655–1671.

LAMOTTE, R. H. and WHITEHOUSE, J. 1986, Tactile detection of a dot on a smooth surface: peripheral neural events, *Journal of Neurophysiology*, **56**, 1109–1128.

LEDERMAN, S. J. 1974, Tactile roughness of grooved surfaces: the touching process and effects of macro- and microsurface structure, *Perception and Psychophysics*, **16**, 385–395.

LEDERMAN, S. J. and TAYLOR, M. M. 1972, Fingertip force, surface geometry, and the perception of roughness by active touch, *Perception and Psychophysics*, **12**, 401–408.

LEDERMAN, S. J., LOOMIS, J. M., and WILLIAMS, D. A. 1982, The role of vibration in the tactual perception of roughness, *Perception and Psychophysics*, **32**, 109–116.

LEVIN, S., PEARSALL, C. and RUDERMAN, R. 1978, Van Frey's method of measuring pressure sensibility in the hand: an engineering analysis of the Weinstein-Semmes pressure aesthesiometer, *Journal of Hand Surgery*, **3**, 211–216.

LUNDBORG, G., GELBERMAN, R. H., MINTEER-CONVERY, M. LEE, Y. F. and HARGENS, A. R. 1982, Median nerve compression in the carpal tunnel–Functional response to experimentally induced controlled pressure, *Journal of Hand Surgery*, **7A**, 252–259.

MOBERG, E. 1990, Two-point discrimination test, *Scandinavian Journal of Rehabilitation Medicine*, **22**, 127–134.

MOUNTCASTLE, V. B., RALBOT, W. H. and KORNHUBER, H. H. 1966, The neural transformation of mechanical stimuli delivered to the monkey's hand, in A. V. S. de Reuck and J. Knight (eds), *Touch, Heat and Pain* (Churchill, London), 325–345.

PETIT, J. and GALIFRET, Y. 1978, Sensory coupling function and the mechanical properties of the skin, in G. Gordon (ed.), *Active Touch* (Pergamon, Oxford), 19–28.

RADWIN, R. G., JENG, O.-J. and GISSKE, E. T. 1993, A new automated tactility test instrument for evaluating hand function, *IEEE Transactions on Rehabilitation Engineering*, **1**, 220–225.

RADWIN, R. G., WERTSCH, J. J., JENG, O.-J. and CASANOVA, J. 1991, Ridge detection tactility deficits associated with carpal tunnel syndrome, *Journal of Occupational Medicine*, **33**, 730–735.

SPINNER, R. J., BACHMON, J. W. and AMADIO, P. C. 1989, The many faces of carpal tunnel syndrome, *Mayo Clinic Proceedings*, **64**, 829–836.

STEVENS, J. C. 1992, Aging and spatial acuity of touch, *Journal of Gerontology*, **47**, 35–40.

THORNBURY, J. M. and MISTRETTA, C. M. 1981, Tactile sensitivity as a function of age, *Journal of Gerontology*, **36**, 34–39.

WOODWARD, K. L. 1993, The relationship between skin compliance, age, gender, and tactile discrimination thresholds in human, *Somatosensory and Motor Research*, **10**, 63–67.