Preliminary Evaluation of a Sensory and Psychomotor Functional Test Battery for Carpal Tunnel Syndrome: Part 1—Confirmed Cases and Normal Subjects

AUTHORS
One-Jang Jeng[a]
Robert G. Radwin[b]*
Dennis G. Fryback[b]

[a]New Jersey Institute of Technology, Newark, NJ 07102;
[b]University of Wisconsin–Madison, 1513 University Avenue, Madison, WI 53706

Two new computer-controlled functional tests were developed, known as the Wisconsin test battery, for carpal tunnel syndrome (CTS). The gap detection sensory test quantifies tactile thresholds for areas of the hand innervated by the median nerve. The rapid pinch and release psychomotor test measures the initiation and control of specific muscles innervated by the median nerve motor branch. Ten confirmed CTS patients (based on electrophysiological parameters and examination; 18 CTS hands) and eight confirmed normal subjects (16 hands) with a similar average age were administered both tests. The CTS patients showed significant functional deficits for both tactility and psychomotor tests. Average CTS performance was 24 to 104% poorer than for the normal subjects, depending on the performance measure. The results indicated high correlations ($r = 0.5$ to 0.8) between median nerve electrophysiological parameters and tactility or psychomotor performance variables. No single functional test variable had sufficient sensitivity for detecting CTS among the subject pool. The combination of the two tests using 95% confidence level cutoff points achieved a sensitivity of 0.78 and a specificity of 0.81. Stepwise discriminant analysis resulted in two performance variables capable of a sensitivity of 0.72 and a specificity of 0.94 for differentiating well-defined CTS subjects from normal subjects. Despite these promising results, limitations of the study include small sample size and subject selection bias. Further studies are needed for verifying the utility of the functional test battery for detecting CTS in a general population.

Keywords: carpal tunnel syndrome, motor, nerve conduction, surveillance, tactility

Carpal tunnel syndrome (CTS) results from a combination of ischemia and compression of the median nerve within the carpal cannel in the wrist.(1) The median nerve is a mixed nerve. It carries motor impulses to the opponens pollicis muscle, and conveys sensory impulses from the palmar surface of the first three fingers and lateral side of the fourth finger. CTS symptoms include pain, loss of motor function, and sensory deficits in the index finger, the long finger, and thumb.(2)

The diagnosis of CTS is usually based on clinical and electrophysiological signs.(3-5) Symptoms typically include diminished or absent cutaneous sensibility, tingling, and nocturnal pain in the distribution of the median nerve. Electrodiagnostic studies often indicate a prolongation of the distal motor latency of the median nerve, slowing of median sensory nerve conduction velocity across

---

*Author to whom correspondence should be addressed.

This research was supported by a grant from the Whitaker Foundation.

the wrist, and denervation of the abductor pollicis brevis muscle.(5,6) The obvious advantage of electrodiagnostic methods such as nerve conduction studies (NCS) and electromyography (EMG) is the absence of reporting bias or any interference from more complex systems. Conduction velocity is most abnormal when the myelin sheath is disrupted.(7) Increasing electrophysiological deficits have been linked to increasing CTS severity.(8) Electrodiagnostic tests, however, are costly, time consuming, and considered noxious by many.

A recent investigation reported that only 4 out of 30 study subjects who had proven CTS were willing to undergo repeat NCS due to the mildly aversive nature of the stimulation.(9) Consequently, NCS is not very suitable for routine monitoring. It is clear that there is a need for a measure of nerve function for monitoring CTS that has high sensitivity and specificity without some of the limitations associated with NCS. Such a test should be easily administered, noninvasive, have high retest reliability, and involve no discomfort for routine testing.

Clinical history and physical examination using provocative tests such as Phalen's sign and Tinel's sign are easy to administer. However, experience shows that they are of limited value in routine monitoring for CTS. The Phalen's and Tinel's signs have sensitivities varying from 25 to 75% and specificities from 47 to 90%.(10) Symptom surveys are commonly used in surveillance studies. The use of symptoms to diagnose CTS is highly sensitive but nonspecific. A study conducted by Katz and colleagues observed that the use of symptoms compatible with CTS had a sensitivity of 0.93 but a specificity of 0.25.(11)

Vibrotactile testing has been proposed as a monitoring instrument for CTS, but these tests were shown to lack sensitivity and specificity.(9,12–13) Abnormal vibration sensation in the digits is believed to be related to a decrease in the number of large myelinated fibers in the median nerve.(14) Although the idea of vibrometry seems attractive, the method suffers from numerous problems. Aaserud, Juntunen, and Matikainen observed a variation of intra-individual vibration sensitivity thresholds from −71 to 159%, both between measurements made at 20-minute intervals and on consecutive days.(15) Fagius and Wahren also found intra-individual variation ranging from −59 to 58% compared with the first value measured.(16) Daily variations in vibrometry have been shown to reduce specificity and sensitivity of the test.(12) The effects of contact pressure, fatigue, and appropriate vibration stimulus waveforms for this test have not yet been clinically evaluated.(17) Another problem with vibrometry is the difficulty in relating deficits in vibration detection thresholds to specific functional deficits. Dellon suggests that vibrotactile tests involve vibration transmission within the entire finger that may have sufficient energy to stimulate receptors at a distance from the test area.(18) Furthermore, no relationship between vibrometry and NCS parameters has been observed.(19)

A series of studies was conducted for investigating subtle sensory and motor maladies associated with CTS using two new tests designed to measure functional deficits in activities resembling manual work activities.(20–24) The objectives of these studies were to evaluate whether the tests could quantify functional deficits in CTS, and whether the tests were sensitive and specific enough to be further tested for future application as a worker-monitoring tool for CTS. These tests together are known as the Wisconsin test battery for CTS.

A new automated aesthesiometer for measuring sensation of a gap in an otherwise smooth surface was developed.(22) This test included both active finger probing (dynamic sense) and passive tactile stimulus detection (static sense). Normal subjects showed a high test-retest reliability, as evidenced by the high correlation (r=0.94) between the test and the retest sessions.(23) A comparison between normal subjects and CTS subjects showed a 100% tactility threshold increase with CTS for dynamic sense, and a 48% increase when the finger passively received the stimulus.(24)

Repetitive finger exertions are often used in industrial activities such as keying switches, operating controls, and squeezing hand tools. A rapid pinch and release test was developed for investigating functional psychomotor deficits associated with CTS.(23) The psychomotor task utilized specific muscle groups of the index finger and thumb innervated by the median nerve. Performance characteristics were speed and force control. Normal subjects performed 25 to 82% better than CTS subjects, depending on the particular performance measure. The test also showed a high test-retest reliability for 13 normal subjects ($0.56 \leq r \leq 0.95$). Performance stabilized quickly and required little or no practice. Median nerve sensory and motor latencies were correlated with pinch rate, time to release the pinch, and time to reinitiate a pinch.(21)

The above studies indicated that the gap detection and psychomotor pinch tests were both reliable and able to detect average differences between normal and CTS subject groups. The results suggest that performance deficits in these tests might be related to the severity of median nerve dysfunction in CTS for individual patients. The current study investigates the optimal use of the gap detection and psychomotor pinch tests for differentiating between individuals with well-defined CTS and normal cases.

METHODS

Tactility Test

The gap aesthesiometer permitted free finger probing while control of contact force was maintained through the use of a precision constant torque balance beam system.(22) Gap size was controlled using a micropositioner and digital encoder. The gap could be made as small as 0.001 mm, and finger contact was controlled within 1 g for forces between 25 and 75 g using a precision balance beam system. Gap displacement, speed, and direction were controlled by a microcomputer. The gap detection test consisted of both dynamic and static stimulus thresholds, tested for 25 and 50 g of contact force.(22,24) Subjects probed the surface with the finger tip for the dynamic test (see Figure 1A). The finger was also held fixed in a support that exposed the distal phalangeal pad while preventing the finger from exerting any force perpendicular to the stimulus platform or from moving the finger across the platform for the static test. The stimulus was automatically raised to contact the finger for the static stimulus.

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 or 0.16 mm, depending on whether the test was static or dynamic, respectively. A converging staircase method of limits was 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. Five gap step size decrements were used. Each gap size was half the magnitude of the previous. A change in gap step size and direction occurred every time a response was different from the previous one. Subjects responded verbally to communicate whether they could or could not detect a gap. The examiner entered the subject's response using the computer keyboard. A threshold determination took less than 5 minutes using this method.

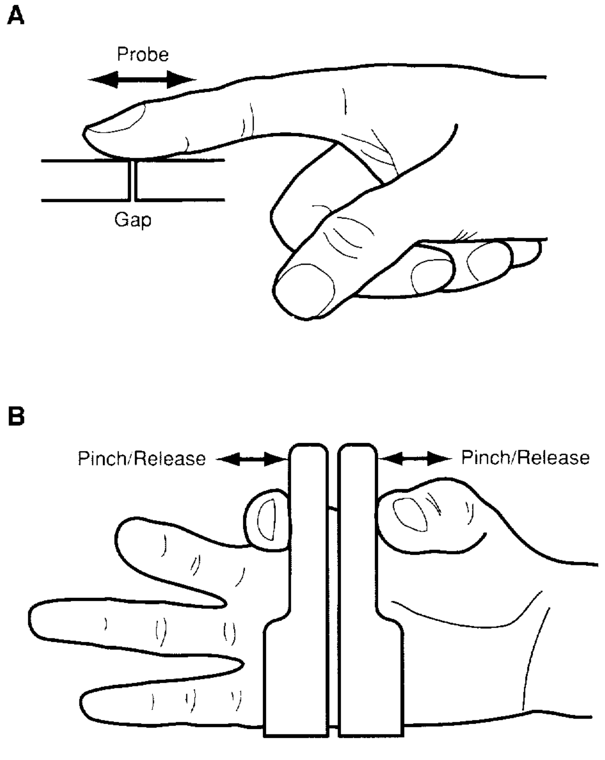

FIGURE 1. Schematic drawings for (A) the gap detection sensory test and (B) the rapid pinch and release psychomotor test

Psychomotor Test

The rapid pinch and release psychomotor test used the thumb and index finger to pinch two aluminum bars instrumented with strain gages.(25) The task involved repetitively pinching and releasing the bars while providing subjects with limited visual and auditory force feedback. The dynamometer was specially designed to measure force independent of the location of the fingers. A schematic drawing of the task is shown in Figure 1B. Pinch force was calculated as the average force measured by the two dynamometer arms. Pulp pinch strength was measured to determine the maximal voluntary contraction (MVC) by taking the greater of two exertions of maximal effort. All force measurements were normalized by expressing force in terms of percentage MVC.

Subjects were instructed to pinch and release as fast as possible while exceeding a predetermined upper force level (F_{UPPER}) and releasing under a lower force level (F_{LOWER}). Discrete visual and auditory feedback was provided on successful pinch or release trials. The task was performed using alternate hands for four conditions of F_{UPPER} (5, 20, 35, and 50 %MVC) for each hand. Performance measures for the psychomotor test are listed in Table I.

The rapid pinch and release psychomotor test began with a practice session where the required upper force level (F_{UPPER}) was randomly selected from 5, 20, 35, or 50 %MVC. Subjects were also allowed to practice as long as desired prior to the beginning of every new trial. Subjects performed the task using alternate hands and completed four conditions of F_{UPPER} (5, 20, 35, and 50 %MVC) for each hand. The lower force level (F_{LOWER}) was fixed at 2 %MVC. The order of experimental conditions was counterbalanced between subjects.

TABLE I. Performance Variables for the Rapid Pinch and Release Psychomotor Test

Variable	Notation	Units
Pinch rate	R_p	pinches/sec
Slope of pinch rate with respect to F_{UPPER}	$\Delta R_p/\Delta F_{UPPER}$	pinches/sec/%MVC
Overshoot force	F_{OVER}	%MVC
Time above F_{UPPER}	T_{UPPER}	msec
Time below F_{LOWER}	T_{LOWER}	msec
Slope of the straight line between the time when F_{UPPER} and F_{LOWER} was exceeded during pinching	M_{INC}	%MVC/sec
Slope of the straight line between the time when exertion level fell below F_{UPPER} and F_{LOWER} during release	M_{DEC}	%MVC/sec

Experimental Procedures

Before participating, subjects provided informed consent and completed a brief demographics questionnaire. CTS symptoms such as numbness, tingling, cold hands, or weakness were also included. The questionnaire also queried whether subjects had previously experienced any hand injuries or disorders including CTS, tendinitis/synovitis, Raynaud's syndrome, nerve injuries, broken bones, etc. Normal subjects were not recruited if they responded in the affirmative to any of the above symptoms or disorders.

All subjects received the gap detection sensory test first and then the rapid pinch and release psychomotor test. Subjects were provided with practice trials for the gap detection test including gap widths they could easily feel and those that they could not detect at all. A 3-second rest period was provided while the gap changed in size before the next trial began. Subjects performed the task for dynamic and static stimulus conditions with a contact force of 25 and 50 g for each hand. The treatment condition order was counterbalanced between subjects.

The time needed for conducting one condition of the gap detection sensory test was 5 minutes. It took a total of 50 minutes to test eight gap detection conditions for each subject. The time for one condition of the rapid pinch and release psychomotor test was approximately 1 minute. It took a total of 15 minutes to test eight pinch and release conditions for each subject. The total time for performing the two functional tests for each subject was 1 hour and 15 minutes, including answering the questionnaire and practice trials.

Subjects

All CTS and normal subjects were examined and received nerve conduction tests. CTS subjects were already confirmed cases who were referred outpatients from the EMG laboratory. The diagnosis of CTS was made according to the regular protocol used by the referring physicians including symptoms based on a history and physical examination and electrodiagnostic parameters compatible with a lesion of the median nerve in the carpal tunnel. Each diagnosis was made on a case-by-case basis. In all cases, no history or physical evidence was suggestive of a confounding neurological disorder such as peripheral neuropathy, cervical radiculapathy, or other nerve entrapments. Ten subjects diagnosed with CTS volunteered for the study. Eight patients had bilateral CTS, providing a total of 18 CTS hands. All the CTS subjects 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 normal subjects were recruited from the university community by posting advertisements. There were five females and three males in the normal subject group, ranging in age between 30 and 52 years. Six of the eight normal subjects described themselves as right-handed and two subjects as left-handed. The mean age for the normal subject group was 41.9 years.

Nerve conduction tests and CTS diagnoses were performed by two qualified physicians using similar test protocols. These included median nerve motor latency and amplitude (8 cm), median nerve antidromic sensory latency and amplitude (13 cm), median nerve transcarpal latency and amplitude (8 cm), and ulnar nerve motor latency (8 cm). Motor latencies were measured to the negative peak using a sensitivity of 1 millivolt/division, and sensory latencies were measured to the negative peak using a sensitivity of 20 microvolts/division Limb temperature was maintained above 32°C.

Normal subjects were volunteers who were screened for abnormal symptoms or disorders. Subjects were not admitted into the study if they indicated a history of confounding hand injuries, disorders, or existence of symptoms related to CTS. Normal subjects were examined and confirmed free of CTS through NCS.

Experimental Design

The experiment consisted of a repeated measures full factorial design using the hand as a random effect variable nested within group, and using age as a covariate (see Table II). Analysis of variance was performed separately for each performance variable of the gap detection test and the rapid pinch and release test. Pearson product correlation was used to find the relationship between the functional test variables and electrophysiological parameters. Factor analysis was used to cluster the functional test variables so that highly correlated variables were grouped as a single factor. Stepwise discriminant analysis was performed to explore the combination of the functional test variables that best predicted the group to which a case belonged.

TABLE II. Experimental Design

Independent Variables	Levels	Conditions
Gap detection test		
Between subjects (group)	2	CTS, normal
Within subjects		
Stimulus	2	dynamic sense, static sense
Contact force	2	25 g, 50 g
Rapid pinch test		
Between subjects (group)	2	CTS, normal
Within subjects		
Stimulus	4	5, 20, 35, 50 %MVC

All hands were treated as individual members in either the normal or the CTS groups. CTS subjects were tested in both hands, even though some subjects had only one symptomatic hand. The asymptomatic hands were not regarded as normal and not used in the comparison between normal and CTS subjects. These asymptomatic hands, however, were included in the correlation and regression analysis between electrophysiological parameters and the gap detection sensory thresholds and psychomotor performance variables.

RESULTS

Average differences between the CTS and normal groups for the gap detection test are contained in Table III. Analysis of variance using age as a covariate demonstrated that all main effects of group, contact force, and stimulus were statistically significant. There was also a significant Group × Stimulus interaction effect ($F(1,32)=9.78$, $p<.01$). CTS subjects had 104% greater average thresholds than the normal subjects for the dynamic sensory stimulus ($F(1,31)=13.64$, $p<.001$). CTS subjects also had 51% greater average static sensory thresholds than the normal subjects ($F(1,31)=13.41$, $p<.001$). No significant Group × Force interaction effect was observed ($F(1,32)=3.51$, $p>.05$). The average dynamic sensory threshold decreased 24%, and static sensory threshold decreased 16% as contact force increased from 25 to 50 g for all hands ($F(1,32)=15.22$, $p<.001$).

TABLE III. Gap Detection Thresholds for Normal and CTS Subjects

		Gap Detection Thresholds (mm)			
		Dynamic Sensory Function		Static Sensory Function	
Contact Force	Group	Mean	SD	Mean	SD
25 g	CTS	0.45	0.18	2.88	1.15
	normal	0.24	0.13	1.79	0.62
50 g	CTS	0.36	0.20	2.29	0.65
	normal	0.16	0.10	1.63	0.50

Age was a significant covariate ($F(1,31)=9.20$, $p<.01$) for the gap detection threshold and contributed 11% of the total variance to the model. The Pearson product correlation indicated that age was significantly correlated with static sensory thresholds ($r=.47$, $p<.01$) but was not correlated with dynamic sensory thresholds ($r=.19$, $p>.1$). Older subjects tended to have slightly greater static sensory thresholds than younger subjects when other factors such as subject group and contact force were controlled.

Significant differences were observed between CTS patients and normal subjects for several performance variables in the rapid pinch and release psychomotor test (see Table IV). CTS hands had an average of 28% less pinch strength than normal hands. Age was a significant covariate for pinch strength ($F(1,31)=4.63$, $p<.05$). Average pinch rate (R_P)was 1.1 pinches/sec (24%) less for the CTS hands than for the normal hands ($p<.01$). Age also was a significant covariate for pinch rate ($F(1,31)=7.09$, $p<.05$). The change in pinch rate with respect to force as F_{UPPER} increased from 5 %MVC to 50 %MVC, $\Delta R_P/\Delta F_{UPPER}$ (pinches/sec/%MVC), was estimated from a linear regression slope using F_{UPPER} as the independent variable and pinch rate (R_P) as the dependent variable. The range of the correlation coefficients for these regression models was between 0.5 and 0.9. $\Delta R_P/\Delta F_{UPPER}$ decreased 0.027 pinches/sec/%MVC (52%) for the CTS hands compared with the normal hands. CTS hands had a 10.9 %MVC (76%) greater overshoot force (F_{OVER}) than the normal hands. Age was a significant covariate for overshoot force for all hands ($F(1,31)=5.50$, $p<.05$). CTS hands had 38 msec (45%) more time above the upper force level, T_{UPPER}, and 28 msec (64%) longer time below the lower force level, T_{LOWER}, than the normal hands. Age was a significant covariate for T_{UPPER} for all hands ($F(1,31)=10.42$, $p<.01$) but not

TABLE IV. Statistical Summary of Psychomotor Performance Variables for F_{UPPER} = 20 %MVC

	Group	N	Mean	SD	F Test
MVC (N)	CTS	18	31.1	9.1	F(1,31)=8.10, p<.01^A
	normal	16	43.3	16.4	
R_P (pinches/sec)	CTS	18	3.6	0.7	F(1,31)=8.98, p<.01^A
	normal	16	4.7	1.0	
$\Delta R_P/(F_{UPPER}$ (pinches/sec/%MVC)	CTS	18	−0.024	0.019	F(1,31)=18.93, p<.001^A
	normal	16	−0.051	0.018	
F_{OVER} (%MVC)	CTS	18	22.7	10.7	F(1,31)=10.64, p<.01^A
	normal	16	13.5	5.5	
T_{UPPER} (msec)	CTS	18	121	26	F(1,31)=20.72, p<.001^A
	normal	16	84	23	
T_{LOWER} (msec)	CTS	18	73	21	F(1,31)=15.80, p<.001
	Normal	16	45	22	

^{A}Age was a significant covariate to the correspondent analysis of variance model.

a significant covariate for T_{LOWER} (F(1,31)=2.32, p>.1).

Pearson correlation coefficients between gap detection sensory thresholds, psychomotor test variables, and electrophysiological parameters are contained in Table V. Gap detection thresholds and psychomotor test variables were significantly correlated with median nerve motor, sensory, and transcarpal latencies. They had poor correlation with ulnar nerve motor latency (p>0.1). Two of the functional performance variables (dynamic sensory threshold and pinch rate) are plotted against median nerve sensory latency in Figure 2. Straight lines were superimposed on the data point according to the linear regression models. Among the functional task parameters, all but M_{INC} and M_{DEC} (see Table I) had significant correlation with median nerve motor, sensory, and transcarpal latencies. F_{OVER} had relatively less correlation with electrophysiological parameters compared with the other psychomotor performance variables. Age was slightly correlated with F_{OVER} and with T_{UPPER}. Pinch strength did not have a significant correlation with any electrophysiological parameters (see Table V).

To investigate the use of the functional tests and their variables for differentiating CTS and normal subjects, cut-off points for normal values were obtained by using the normal subject means and standard deviations (SD) for each test performance variable. Each performance variable was treated as an individual score. A 95% confidence interval was defined as the upper boundary for normal test values. Therefore, the criterion for a CTS case for each variable was the normal mean plus 1.96 × SD. For individual scores the dynamic sensory threshold at 25 g had the best sensitivity and specificity compared with any of the other individual variables, resulting in a sensitivity of 0.44 and a specificity of 0.94. Combinations of all the variables were tried to obtain the scoring system. A positive case was defined as at least one positive test score for any of the variables. For example, a positive case in the psychomotor test resulted from a positive test score in any one of the psychomotor performance variables. Results of this analysis are contained in Table VI. The combined test using only gap detection thresholds had a sensitivity of 0.61 and a specificity of 0.88. The combined test using only psychomotor performance variables resulted in a sensitivity of 0.61 and a specificity of 0.94. A sensitivity of 0.78 and a specificity of 0.81 was obtained when gap detection threshold and psychomotor performance test variables were used together. These tests were also investigated using different cut-off criteria. The sensitivity decreased to 0.56 and the specificity increased to 0.94 as the criterion was raised to 2.58 × SD above the mean of the normal subjects (see Table VI).

Factor analysis showed that performance variables could be clustered into two factors. Both dynamic and static sensory thresholds, and all psychomotor performance variables except M_{INC} and M_{DEC}, could be grouped into a single factor. The remaining M_{INC} and M_{DEC} could be grouped into the other factor. The total variance accounted for by these two factors is shown in Table VII. The overall variance

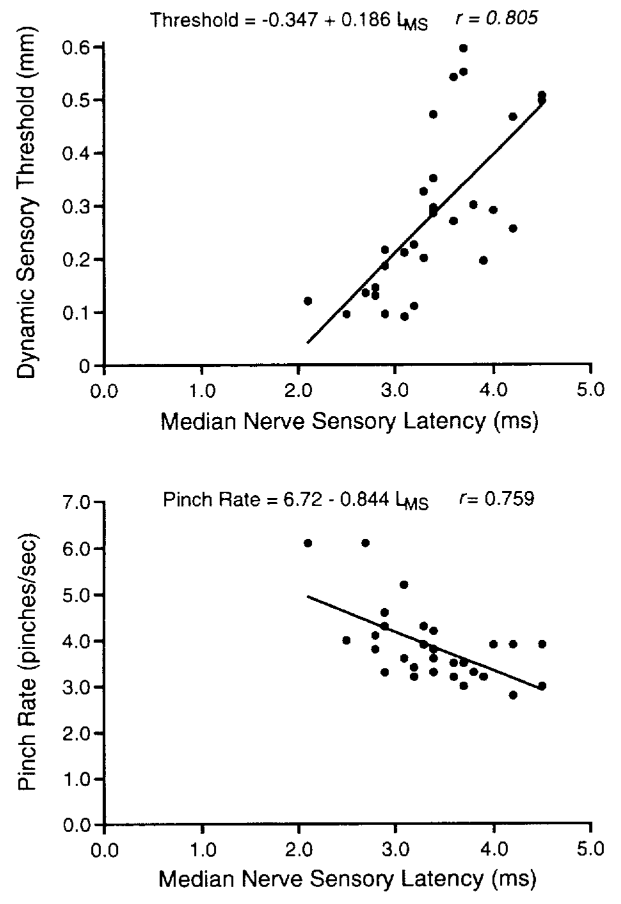

FIGURE 2. Scatter plots of median nerve sensory latency versus functional performance parameters. The data were pooled from both CTS and normal hands. The regression models had F(1,27) = 25.47, p<.001 for the median nerve sensory latency versus dynamic sensory threshold, and F(1,27) = 15.59, p<.01 for the median nerve sensory latency versus pinch rate.

TABLE V. Correlation Between Electrophysiological Parameters and Functional Test Variables

	Median Nerve Latencies			Ulnar Nerve Latencies	
	Motor	Sensory	Transcarpal	Motor	Age
Gap detection test					
Dynamic threshold	0.783^{A}	0.805^{A}	0.659^{A}	0.039	0.191
Static threshold	0.716^{A}	0.706^{A}	0.532^{A}	0.049	0.470^{B}
Psychomotor pinch test					
R_P	-0.619^{A}	-0.759^{A}	-0.572^{A}	−0.107	−0.282
$\Delta R_P/\Delta F_{UPPER}$	0.599^{A}	0.729^{A}	0.619^{A}	0.175	0.093
F_{OVER}	0.387^{C}	0.357^{C}	0.372^{C}	−0.133	0.392^{C}
T_{UPPER}	0.572^{A}	0.595^{A}	0.630^{A}	−0.096	0.484^{B}
T_{LOWER}	0.622^{A}	0.701^{A}	0.506^{B}	−0.147	0.250
Pinch strength test					
Strength	−0.313	−0.214	−0.293	0.076	−0.300

$^{A}P< .001$
$^{B}P< .01$
$^{C}P< .05$

TABLE VI. Sensitivity and Specificity for Different Test Combinations and Cut-off Criteria

		Test Combination				
Cut-Off Criteria		Dynamic Sense	Static Sense	Dynamic and Static Tests	Psychomotor Test	All Tests
Mean	sensitivity	1.00	0.94	1.00	1.00	1.00
	specificity	0.50	0.50	0.31	0.13	0.13
Mean+1 × SD	sensitivity	0.72	0.67	0.83	0.78	1.00
	specificity	0.81	0.81	0.69	0.38	0.31
Mean+1.96 × SD	sensitivity	0.44	0.44	0.61	0.67	0.78
	specificity	0.94	0.88	0.88	0.94	0.81
Mean+2.58 × SD	sensitivity	0.44	0.33	0.50	0.44	0.56
	specificity	0.94	1.00	0.94	1.00	0.94

accounted for by the two clustered factors was 71%. The two clustered factors had a high internal consistency (Carmine's theta = 0.91). The results of the factor analysis confirmed the findings from the Pearson correlation matrix that these functional performance variables were highly correlated with each other. Based on the results of the Pearson correlation and factor analysis, specific variables were selected to investigate their use further for detecting CTS subjects.

Stepwise discriminant analysis was performed to explore the combination of functional test variables that would best classify well-defined CTS subjects and normal subjects. Dynamic and static sensory thresholds for both 25 and 50 g of contact force, and all psychomotor performance variables except M_{INC} and M_{DFC}, were initially included in the analysis. Forward selection was applied to the stepwise discriminant analysis. Variables were entered if the F value was greater than 4.00 ($p<0.05$ for a sample size of 60 observations) and was removed if the F value was less than 3.996. The F-to-enter for each variable not in the current equation was computed using a one-way analysis of variance, where the covariates were the variables in the current equation. Of all the variables, only time below the F_{LOWER} and the $\Delta R_P/\Delta F_{UPPER}$ were selected into the final discriminant function.

For 18 diagnosed CTS cases, 13 cases were correctly assigned to their corresponding category. Therefore, the sensitivity of the discriminant function for detecting CTS was 0.72. Fifteen of the 16 normal cases were correctly assigned to their corresponding category, so the specificity of the discriminant function was 0.94. The resulting linear discriminant function canonical variable was

$$CTS = -1.07+32.23 \times \Delta R_P/\Delta F_{UPPER}\ (\text{pinches} \times \text{sec}^{-1} \times \%MVC^{-1})+0.04 \times T_{LOWER}\ (\text{msec})$$

($F(2,31)=15.29$, $p<.001$). The mean canonical variable value was −1.02 for normal subjects and +0.91 for the CTS subjects. A histogram based on the canonical variable for all subjects is plotted in Figure 3.

A receiver operating characteristic (ROC) curve(26) was constructed using the continuously distributed canonical variable data from all hands (see Figure 4). The binormal ROC curve was fitted using a maximum likelihood estimation for the categories denoted as points on the graph. The categories were derived from the canonical variable data such that the fraction of normal cases plus the fraction of abnormal cases in each category was approximately constant. Results using the canonical variables revealed that the estimated area beneath the fitted ROC curve was 0.930 with an SD of 0.043.

TABLE VII. Total Variance of Performance Variables Accounted for by Factor Analysis

Factors	Performance Variables	R^2
Factor A	dynamic threshold at 25 g	0.80
	dynamic threshold at 50 g	0.73
	static threshold at 25 g	0.72
	static threshold at 50 g	0.65
	pinch rate	0.79
	pinch rate slope	0.48
	overshoot force	0.58
	time above F_{UPPER}	0.72
	time below F_{LOWER}	0.66
Factor B	slope of force when pinching	0.82
	slope of force when releasing	0.90
Overall		0.71

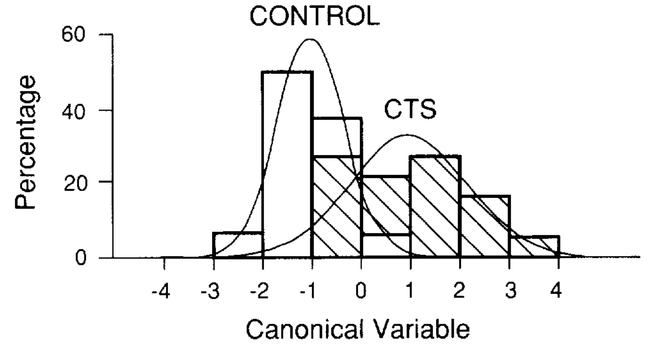

FIGURE 3. Histogram of canonical variables for CTS and normal subject samples. Canonical variable = $-1.07 + 32.23 \times \Delta R_P/\Delta F_{UPPER} + 0.04 \times T_{LOWER}$.

DISCUSSION

The results showed that the psychomotor and sensory tests can reveal individual functional deficits associated with CTS. Since these two tests had functional resemblance to many work-related activities such as detecting surface defects or operating tools, the results suggest that workers suffering from CTS may experience similar performance deficits in these types of work activities.

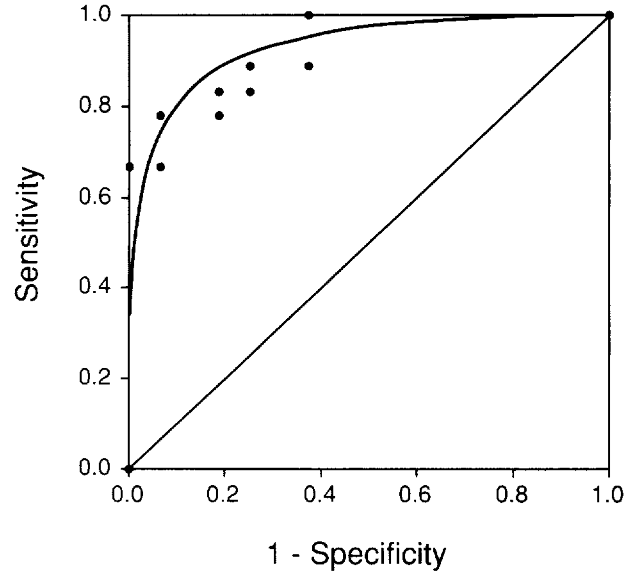

FIGURE 4. ROC curve using the canonical variable data from CTS and normal subjects

The results of the rapid pinch and release psychomotor test were compared with a previous investigation(23) that included only the psychomotor test. The current study included both sensory and psychomotor tests, but there were no replicates. The results for the psychomotor performance variables were very similar to previous findings. The current study observed an overall pinch strength difference between the normal group and the CTS group (see Table III). Such a difference was not observed in the previous study ($F(1,46) = 2.85$, $p > .05$). One hypothesis as to the difference between the current and the previous study is that there were more severe CTS cases in the current study than in the previous study. Studies have shown that decreased muscle strength occurs at late stages of CTS, and not until measurable changes have already occurred in sensory function.(27) Since all 10 subjects in the CTS group were female, and 3 out of the 8 normal subjects were male, the strength difference observed in the current study could also be attributed to a gender effect. However, performance for the rapid pinch and release psychomotor test were not confounded with pinch strength since all the test parameters were normalized using %MVC rather than absolute force exertions.

Strong correlations were observed between median sensory, motor, and transcarpal nerve conduction latencies and the gap detection thresholds and most of the psychomotor test performance variables. While the gap detection test simply tested sensory function, the psychomotor test involved integrating motor and sensory function. A strong correlation was expected between the sensory thresholds and sensory latencies. Since the correlation between median nerve sensory latencies and motor latencies was 0.72 ($p < 0.001$), the high correlation between sensory thresholds and motor latencies could be because the hands with high sensory latencies also tended to have high motor latencies. There was also a strong correlation between psychomotor performance parameters and motor and sensory latencies. This may have occurred because the psychomotor pinch test involves not only fine motor control but also sensory feedback. Pinch strength, however, did not have a significant correlation with electrophysiological parameters. This suggests that pinch strength was not a good indicator for CTS. Previous studies have shown that decreased muscle strength in CTS occurs late, and usually not until measurable sensory deficits have already occurred.(27)

Since the correlations were obtained from the pooled CTS and normal data, concerns are raised whether the strong correlations between the median nerve latencies and the functional performance variables were the result of two clusters of extreme data. The scatter plots in Figure 2, however, indicate that the median nerve sensory latency data were widely distributed within the latency range. Therefore, the correlation results were not likely to be affected by the pooled data approach. The existence of a linear relationship between the median nerve parameters and the functional performance variables may suggest that the functional test measurement can predict the status of the median nerve. However, further studies are needed, especially involving larger unbiased samples, before the conclusion could be made.

Analyses using different cut-off criteria and different test combinations suggested that none of the individual variables alone were sensitive enough to detect CTS. The test paradigm involved both the gap detection threshold and psychomotor pinch tests, for an upper normal boundary of 1.96 × SD above the normal group mean, resulted in a sensitivity of 0.78 and a specificity of 0.81. Changing the criteria for obtaining different sensitivity and specificity and reducing the test item to just the psychomotor pinch test may be considered, depending on the economics of misses and false positives in a CTS monitoring program.

Two psychomotor parameters, $\Delta R_P/\Delta F_{UPPER}$ and T_{LOWER}, were selected using stepwise discriminant analysis for differentiating between CTS subjects and normal subjects. The linear discriminant function provides a direct estimate of the canonical variable to predict whether a case belongs to the CTS or the normal category. While the dynamic sensory threshold was, by itself, the second best diagnostic indicator, it was not selected into the discriminant function. This occurred because the dynamic sensory threshold was highly correlated with the psychomotor test variables. Consequently, after $\Delta R_P/\Delta F_{UPPER}$ was entered into the discriminant function, the dynamic sensory threshold was deleted. The choice of $\Delta R_P/\Delta F_{UPPER}$ suggested that just one F_{UPPER} was insufficient for the psychomotor pinch test to detect CTS. Since there were a limited number of CTS and normal subjects in the current study, the actual canonical variables might change if a larger sample was studied, but the results reveal the importance of including both motor and sensory parameters.

Although vibration threshold tests have been suggested for monitoring CTS, there have been only a few studies investigating the sensitivity and specificity of vibrometry. A study by Gerr found sensitivities of 0.61 and 0.57, for specificities of 0.70 and 0.80, respectively, after 10 minutes of wrist flexion.(9) Without wrist flexion, sensitivity was 0.35 and 0.28. Lundborg and colleagues found that 44 out of 54 hands neurophysiologically classified as positive for CTS had abnormal digital vibrograms, and 14 out of 26 hands with normal neurophysiological results had abnormal digital vibrograms.(28) The sensitivity was 0.83 and the specificity was 0.46 when using neurophysiological parameters as the gold standard. Since all of their subjects were patients who complained of CTS symptoms, it was difficult to compare their findings with the current study. The above two studies were both conducted in laboratory settings. Werner et al. correlated vibrometry using single frequency (120 Hz)(29) and multiple frequency(30) with nerve conduction study measures for CTS among 130 and 167 industrial workers, respectively. They found a significant yet weak correlation (r ranged between 0.22 and 0.37) between vibrometry thresholds and the nerve conduction latencies. Their results suggest that vibrometry screening for early carpal tunnel syndrome might not be effective. The clinical history and physical exam are commonly used to monitor for CTS. The National Institute for Occupational Safety and Health (NIOSH) case definition for work-related CTS requires the presence of median nerve symptoms, one or more occupational risk factors, and objective evidence of CTS including physical examination findings or nerve conduction tests diagnostic of CTS.(31) The NIOSH case definition achieved a sensitivity of 0.67 and a specificity of 0.58 when nerve conduction tests were used as the gold standard.(11) Since the current study used a different experimental paradigm and study population for the functional test battery from the above-mentioned studies, it is not possible to compare the sensitivity and specificity directly between these different tests.

The ROC curve is a graphical method for depicting the trade-off between the true-positive rate (sensitivity) and the false-positive rate (1-specificity) of a test.(32) The choice of an appropriate sensitivity with its correspondent specificity depends on the objectives of the test to be used. The trade-off would depend on whether the test was used for epidemiological surveillance, screening, or diagnostic purposes. As a diagnostic test for confirming a disorder or disease on a suspected case, both high sensitivity and high specificity are needed to avoid miss-diagnosis. As a monitoring test for identifying possible cases, a higher sensitivity is desired. Too much sensitivity with low specificity, however, would result in an abundance of false-positive cases. In the case of occupational monitoring for upper limb musculoskeletal disorders, a test that is highly sensitive to functional deficits associated with CTS is desirable; employees displaying these deficits should be more carefully monitored. The current results, although for a limited sample, shows promise for improved sensitivity with specificity using a combination of parameters for a positive case.

This study has several limitations. Because of practical considerations, subjects recruited in the patient and normal subject groups were not sampled using typical case-control approaches.Therefore, the results might have been confounded with unequal distribution of gender, age, and other factors between the CTS and normal subject groups. However, none of these effects was observed.

Two CTS subjects had unilateral CTS. Those two subjects either had to be eliminated or each hand had to be treated as an individual subject to construct a complete block design. Eliminating two unilateral CTS cases would have reduced the CTS data by 12% because of the relatively small sample size. Hands were therefore treated as individual subjects. The magnitude of the difference between the CTS and normal subjects for the functional tests suggests that the results are robust despite the potential hand correlation bias. Residual analysis revealed no trends indicating that the pooled statistical model was apt. The data were analyzed separately for both dominant and nondominant hands. Even with a small sample of 18 (10 CTS and 8 normal hands) for the dominant hand and 16 (8 CTS and 8 normal hands) for the nondominant hand, significant dynamic sensory threshold differences were individually observed between CTS and normal hands for the dominant hand ($F(1, 15) = 9.68$, $p<.01$) and nondominant hand ($F(1,13) = 5.34$, $p<.05$). The static sensory threshold was significantly different between the CTS and normal hands ($F(1, 15) = 6.10$, $p<.05$ for the dominant hands and $F(1,13) = 10.90$, $p<.01$). Four out of five comparisons between the CTS and normal hands were still significant for either dominant hand data or nondominant hand data. The two comparisons that did not achieve statistically significant levels were F_{OVER} for the dominant hand and R_p for the nondominant hand, but the trend did not change. Consequently, the results were very similar to the combined dominant/nondominant hand data set. It is anticipated that statistical significance for those two comparisons would have been achieved if a larger sample were used. Correlation analysis also showed similar results between the hand-separated data sets and the hand-combined data set.

Since a limited number of CTS subjects and normal subjects were tested, a misclassification by the functional tests could change the sensitivity and specificity for detecting CTS. A larger sample will give a more reliable estimate of the sensitivity and specificity of the functional test battery. CTS subjects were recruited from patients referred to the EMG clinics for electrophysiological confirmation. The sensitivity of the functional tests for detecting CTS may be raised since their disorders were well developed.(33) Normal subjects were confirmed by the absence of CTS symptoms, negative NCS results, and absence of other disorders that might elevate the test specificity. Although commonly used, this subject selection approach has what is referred to as a spectrum bias, since only two extremes of the distribution of CTS severity were sampled.(34) A test that is highly sensitive to well-developed diseases or disorders may not necessarily be able to detect them in the early stages. A test initially regarded as sensitive and specific for a bimodally distributed population may not be valid after its introduction into practice for a more uniformly distributed population.

With the above limitations, results of the current study should be regarded as preliminary and tentative but quite promising. Further studies are needed to incorporate a larger sample size and recruit workers from jobs with a high incidence of CTS for a wider distribution of the disorder. The utility of the rapid pinch and release psychomotor test and the gap detection sensory test as monitoring instruments could thereby be determined more thoroughly.

CONCLUSIONS

This investigation showed promise for further studying the application of the gap detection and psychomotor pinch tests to monitor workers exposed to risk factors associated with CTS. CTS patients showed significant functional performance deficits (24 to 104%) for the psychomotor pinch and gap detection sensory tests. The simplified test paradigm for the psychomotor pinch test in the current study was adequate, since the test results were equivalent to those of the previous study, which had three replicates for each test condition. The results indicated high correlations (0.5 to 0.8) between median nerve electrophysiological parameters, gap detection thresholds, and psychomotor performance variables. No single variable from any one of these functional tests was sensitive enough for detecting CTS. The combination of the two tests achieved a sensitivity of 0.78 and a specificity of 0.81. A stepwise discriminant analysis indicated that use of multiple performance variables could improve specificity with sensitivity and resulted in a sensitivity of 0.72 and a specificity of 0.94 for differentiating well-defined CTS subjects from normal subjects.

The limitations of this study included small sample size, treating hands as individual subjects, and subject selection spectrum bias. Therefore, results of the current study are preliminary and tentative. Further studies should be done using a larger sample of workers from jobs with a high incidence of CTS to determine more conclusively the utility of the rapid pinch and release psychomotor test and the gap detection sensory test.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Robert Harmon and Dr. Barend Lotz for performing nerve conduction studies and referring CTS patients for this study.

REFERENCES

1. **Lundborg, G., R.H. Gelberman, M. Minteer-Convery, Y.F. Lee, et al.:** Median nerve compression in the carpal tunnel—functional response to experimentally induced controlled pressure. *J. Hand Surg. [Am].* *7*:252–259 (1982).

2. **Phalen, G.S.:** The carpal-tunnel syndrome. Clinical evaluation of 598 hands. *Clin. Orthop. 83*:29–40 (1972).

3. **Phalen, G.S.:** The carpal-tunnel syndrome. *J. Bone Joint Surg. [Am]. 48*: 211–228 (1966).

4. **Dawson, D.M., M. Hallett, and L.H. Millender:** *Entrapment Neuropathies.* Boston: Little, Brown and Co., 1983.

5. **Kimura, J.:** *Electrodiagnosis in Diseases of Nerve and Muscle: Principles and Practice.* 2nd ed. Philadelphia, PA: F.A. Davis, 1989.

6. **Stevens, J.C.:** AAEE minimonograph #26: The electrodiagnosis of carpal tunnel syndrome. *Muscle Nerve 10*:99–113 (1987).

7. **Moody, L., J. Arezzo, and D. Otto:** Evaluation of workers for early peripheral neuropathy. *Semin. Occup. Med. 1*:153–162 (1986).

8. **Mackinnon, S.E. and A.L. Dellon:** *Surgery of the Peripheral Nerve.* New York: Thieme, 1988.

9. **Gerr, F.E.:** *Quantitative Assessment of Carpal Tunnel Syndrome* (Final performance report 5K01OH00098-03). Cincinnati, OH: National Institute for Occupational Safety and Health, 1994.

10. **Katz, J.N., M.G. Larson, A. Sabra, C. Krarup, et al.:** Carpal tunnel syndrome: Diagnostic utility of the history and physical examination findings. *Ann. Intern. Med. 112*:321–327 (1990).

11. **Katz, J.N., M. Larson, A.H. Fossel, and M.H. Liang:** Validation of a surveillance case definition of carpal tunnel syndrome. *Am. J. Public Health 81*:189–193 (1991).

12. **White, K.M., J.J. Congleton, R.D. Huchingson, R.J. Koppa, et al.:** Vibrometry testing for carpal tunnel syndrome: A longitudinal study of daily variations. *Arch. Phys. Med. Rehabil. 75*:25–28 (1994).

13. **Winn, F.J. and V. Putz-Anderson:** Vibration thresholds as a function of age and diagnosis of carpal tunnel syndrome: A preliminary report. *Exp. Aging Res. 16*:221–224 (1990).

14. **Bleecker, M.L. and J. Agnew:** New techniques for the diagnosis of carpal tunnel syndrome. *Scand. J. Work, Environ. Health 13*:385–388 (1987).

15. **Aaserud, O., J. Juntunen, and E. Matikainen:** Vibration sensitivity thresholds: methodological considerations. *Acta Neurol. Scand. 82*:277–283 (1990).

16. **Fagius, J. and L.K. Wahren:** Variability of sensory threshold determination in clinical use. *J. Neurol. Sci. 51*:11–27 (1981).

17. **Harada, N. and M.J. Griffin:** Factors influencing vibration sense thresholds used to assess occupational exposures to hand transmitted vibration. *Br. J. Ind. Med. 4*:185–192 (1991).

18. **Dellon, A.L.:** Clinical use of vibratory stimuli to evaluate peripheral nerve injury and compression neuropathy. *Plast. Reconstr. Surg. 65*:466–476 (1980).

19. **Merchut, M.P., M.A. Kelly, and S.C. Toleikis:** Quantitative sensory threshold testing in carpal tunnel syndrome. *Electromyogr. Clin. Neurophysiol. 30*:119–124 (1990).

20. **Radwin, R.G., J.J. Wertsch, O.-J. Jeng, and J. Casanova:** Ridge detection tactility deficits associated with carpal tunnel syndrome. *J. Occup. Med. 33*:730–735 (1991).

21. **Rodriquez, A.A., R.G. Radwin, and O.-J. Jeng:** Median nerve electrophysiologic parameters and psychomotor performance in carpal tunnel syndrome. *Electromyogr. Clin. Neurophysiol. 33*:311–319 (1993).

22. **Radwin, R.G., O.-J. Jeng, and E.T. Gisske:** A new automated tactility test instrument for evaluating hand function. *IEEE Trans. Rehabil. Eng. 1*: 220–225 (1993).

23. **Jeng, O.-J., R.G. Radwin, and A.A. Rodriquez:** Functional psychomotor deficits associated with carpal tunnel syndrome. *Ergonomics 37*: 1055–1070 (1994).

24. **Jeng, O.-J. and R.G. Radwin:** A gap detection tactility test for measuring sensory deficits associated with carpal tunnel syndrome. *Ergonomics 38*: 2588–2601 (1995).

25. **Radwin, R.G., G.P. Masters, and F.W. Lupton:** A linear force summing hand dynamometer independent of point of application. *Appl. Ergonomics 22*: 339–345 (1992).

26. **Hanley, J.A. and B.J. McNeil:** The meaning and use of the area under a receiver operating characteristic (ROC) curve. *Radiology 143*:29–36 (1982).

27. **Gelberman, R.H., R.M. Szabo, R.V. Williamson, and M.P. Dimick:** Sensibility testing in peripheral-nerve compression syndromes. *J. Bone Joint Surg. [Am]. 65*:632–638 (1983).

28. **Lundborg, G., A.-K. Lie-Stenström, C. Sollerman, T. Strömberg, et al.:** Digital vibrogram: A new diagnostic tool for sensory testing in compression neuropathy. *J. Hand Surg. [Am]. 11*:693–699 (1986).

29. **Werner, R.A., A. Franzblau, and E. Johnston:** Quantitative vibrometry and electrophysiological assessment in screening for carpal tunnel syndrome among industrial workers: a comparison. *Arch. Phys. Med. Rehabil. 75*: 1228–1232 (1994).

30. **Werner, R.A., A. Franzblau, and E. Johnston:** Comparison of multiple frequency vibrometry testing and sensory nerve conduction measures in screening for carpal tunnel syndrome in an industrial setting. *Am. J. Phys. Med. Rehab. 74*:101–106 (1995).

31. **Matte, T.D., E.L. Baker, and P.A. Honchar:** The selection and definition of target work-related conditions for surveillance under SENSOR. *Am. J. Public Health 79(suppl)*:21–25 (1989).

32. **Institute of Medicine:** *Assessing Medical Technologies.* Washington, DC: National Academy Press, 1985.

33. **Sox, H.C., M.A. Blatt, M.C. Higgins, and K.I. Marton:** *Medical Decision Making.* Boston: Butterworths, 1988.

34. **Ransohoff, D.F. and A.R. Feinstein:** Problem of spectrum and bias in evaluating the efficacy of diagnostic tests. *N. Eng. J. Med. 299*:926–930 (1978).