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Preliminary Evaluation of a Sensory and Psychomotor Functional Test Battery for Carpal Tunnel Syndrome: Part 2—Industrial Subjects

This study evaluated the Wisconsin functional sensory and psychomotor test battery for carpal tunnel syndrome (CTS). Subjects were 27 employees recruited from a food processing plant. Both hands of all subjects were examined and categorized by presence or absence of symptoms and nerve conduction study (NCS) findings (Symptom⁻/NCS⁻, Symptom⁺/NCS⁻, Symptom⁻/NCS⁺, and Symptom⁺/NCS⁺). Symptom⁻/NCS⁻ category hands had significantly better performance (15–60%) for most of the functional test battery variables than Symptom⁺/NCS⁺ category hands. A significant gap detection threshold difference (32%) was observed between NCS⁺ and NCS⁻ hands regardless of symptoms, with NCS⁻ having impaired performance. No significant effect of CTS symptoms on performance was observed. Stepwise discriminant analysis was used to select the best variables to differentiate between groups. The ratio of the change in pinch rate with respect to required pinch force differentiated NCS⁺ from NCS⁻ hands, with a sensitivity of 0.71 and a specificity of 0.68. The same variable had a sensitivity of 0.74 and specificity of 0.83 for distinguishing Symptom⁻/NCS⁻ hands from all other categories. Pinch rate had a sensitivity of 0.82 and a specificity of 0.81 for separating Symptom⁺/NCS⁺ hands from all other categories. Use of both gap detection threshold and the ratio of the change in pinch rate with respect to required pinch force could best differentiate Symptom⁺/NCS⁺ from Symptom⁻/NCS⁻ cases for a sensitivity of 0.91 and specificity of 0.87. Outcomes could not be generalized to a specific work population but demonstrate that the non-invasive test battery may be useful for providing objective measures of deficits associated with CTS symptoms and electrophysiological parameters.

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

Although there is no universally accepted case definition, the diagnosis of carpal tunnel syndrome (CTS) is usually based on both examination and electrophysiological findings.⁽¹⁻³⁾ CTS symptoms include numbness and tingling in the distribution of the median nerve that characteristically increase or occur at night or with static grasp. Electrodiagnostic findings may include a prolongation of the distal motor latencies of the median nerve, slowing of

median sensory nerve conduction velocity across the wrist, and denervation of the abductor pollicis brevis muscle.⁽³⁻⁵⁾

Practical tools in active surveillance programs are needed to detect CTS with high sensitivity and specificity. Such tools could be used to reveal potential CTS cases, or they may be used to monitor the results of surgical, medical, or ergonomic interventions. Because of the high incidence of CTS in some industries,^(6,7) it may be beneficial to monitor workers in high risk jobs periodically using suitable instruments for early detection of the disorder before it progresses, and control exposure to CTS stress factors and avert exacerbation of the problem. Currently there is no suitable instrument available.

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Nerve conduction studies (NCS) are considered the most objective diagnostic tests for CTS. The discomfort, time, expense, and high level of training required to administer them make NCS an unlikely candidate for routine evaluation of asymptomatic workers. 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.⁽⁸⁾

A series of studies was conducted for investigating functional deficits associated with CTS using an experimental instrument consisting of two computerized tests designed and developed at the University of Wisconsin-Madison to measure psychomotor and sensory function involving tasks resembling manual work activities.⁽⁹⁻¹²⁾ These studies showed that the Wisconsin psychomotor and sensory test battery was able to detect average differences between patients diagnosed having CTS and normal subjects free of CTS, and that performance was correlated with nerve conduction parameters of the median nerve.

A recent study indicated that the Wisconsin test battery could differentiate well-defined CTS cases from confirmed normal subjects with a sensitivity of 0.72 and a specificity of 0.94.⁽¹³⁾ Studies to date utilized CTS out-patients who were referred from a university hospital electromyography (EMG) laboratory and normal volunteers who were confirmed as having nerve conduction study parameters suggesting normal median nerve function, no CTS symptoms, and were free of other disorders. As a result, the test sensitivity and specificity for detecting CTS could have been elevated, since only two extremes of the distribution of CTS severity were sampled.⁽¹⁴⁾ This effect is sometimes referred to as a spectrum bias.⁽¹⁵⁾ Spectrum bias in a study might produce misleading results, so that a test initially regarded as sensitive and specific for a bimodally distributed population may be less useful after its introduction into practice for a more uniform or otherwise distributed population. Furthermore, a test that is highly sensitive to well-developed diseases or disorders may not be able to detect them in the early stages.

To ascertain whether the Wisconsin CTS battery could be useful for testing an industrial population more widely distributed in CTS severity and symptoms than the population previously studied, such as in a large-scale longitudinal study, it was necessary to perform a controlled investigation involving a more distributed subject group. The purpose of the current study was to evaluate the sensory and psychomotor functional test battery using subjects from an industrial population with high prevalence of CTS. The study involved selecting subjects into specific categories to achieve a more uniformly distributed sample of CTS symptoms and nerve conduction parameters. The sample was not intended to represent any particular population. Subjects were tested for functional deficits, clinical evaluation, and nerve conduction parameters. Results from the Wisconsin functional tests were compared with previous findings involving a bimodally distributed normal/patient population.

METHODS

Subjects

The experiment was conducted in a midwestern United States food processing plant. An advertisement for subjects was posted on the plant bulletin board. Volunteers were queried by a nurse in the employee health department about sustained CTS symptoms such as numbness, tingling, or nocturnal pain in the median nerve innervated area of the thumb, index finger, and middle finger, identifying conditions that might temporarily follow fatigue or

cold exposure. Volunteers were then categorized into three groups: (1) those reporting no CTS-related symptoms, (2) those reporting symptoms consistent with CTS but no medical confirmation, and (3) those reporting CTS symptoms and who had been diagnosed as having CTS, but who did not undergo carpal tunnel release surgery. This categorization approach was applied to help ensure a diverse subject sample and to provide a sufficient number of subjects with positive and negative symptoms for the study while using a small subject pool.

There were 41 volunteers, and 28 were selected for the study based on the categorization described. Volunteers who had reported a history of peripheral neuropathies, fractures, severe burns, arthritis, diabetes, and carpal tunnel surgery were not included. A total of 6 volunteers reported no CTS symptoms, 31 volunteers self-reported CTS symptoms but no medical confirmation, and 4 volunteers reported CTS symptoms and medical confirmation based on their employee records. Because there were many more symptomatic volunteers than symptom-free or CTS-confirmed volunteers, some volunteers reporting only CTS symptoms were randomly turned down. The final subject distribution for the study included 5 subjects free of CTS symptoms, 20 subjects reporting CTS symptoms, and 3 subjects with medical records of CTS. One symptomatic subject withdrew from the study while undergoing the NCS.

There were 14 female subjects and 13 male subjects in this study. All 27 subjects described themselves as right-handed. The age range for the sample was between 23 and 57 years (mean = 40.2 years). As many volunteers as possible were scheduled either before or after their shifts so lost production could be minimized. Volunteers were paid their regular hourly salary for participating.

When subjects arrived for testing, hand surface temperature was measured by contacting a thermistor temperature probe against the index finger pad to ensure it was at least 32°C. A heating pad was used to warm the hands if necessary. All subjects were administered the functional test first, followed by clinical evaluation, and then electrodiagnostic evaluation. The experimenters were blind to the particular selection categorization for each subject.

Medical Evaluation

Every participant completed a questionnaire with the assistance of a physician. The questionnaire included information relating to demographics, prior injuries of the upper extremity, past medical history (e.g., diabetes, arthritis, thyroid disease, Raynaud's disease, and renal disease), and the temporal pattern and circumstances associated with possible CTS symptoms for each hand. Symptoms such as tingling, numbness, pain, perceived weakness, and clumsiness were evaluated. Data were taken pertaining to the symptomatic areas of the hand, the frequency of symptoms, and activities involved when symptoms were present. A self-reported hand diagram was completed by each subject with the examiner in attendance. Semmes-Weinstein monofilaments (five filament kit) testing was performed using the volar aspect of the distal thumb, index, and little finger.⁽¹⁶⁾ Calluses present on examination were noted. Thenar atrophy, defined as concavity of the thenar muscle group along the plane parallel to the palm, was scored as absent or present. The Tinel's sign was evoked by percussing the distal wrist crease from a height of 12 cm with the square end of a reflex hammer five times. Phalen's test was performed by asking patients to passively flex both wrists 90° with the dorsal aspects of their hands held in apposition for 1 minute. Positive response to Tinel's and Phalen's signs required pain or paresthesia in at least one digit innervated by the median nerve.⁽¹⁷⁾ The provocative test outcomes were considered by the examining physician, in addition to the symptom questionnaire, and used in objectively evaluating the

presence or absence of symptoms consistent with CTS; however, positive outcomes in provocative tests were neither necessary nor sufficient criteria for ascertaining the presence of CTS symptoms.

Electrodiagnostic Evaluation

NCS were performed bilaterally for all subjects. Testing consisted of (1) median and ulnar transcarpal studies using palmar stimulation and a 3-cm bar recording electrode at 8 cm from the wrist (a 10-cm distance was used when hands were too large for the 8-cm separation); (2) median and ulnar motor studies with the active recording electrodes over the thenar and hypothenar eminences at 8 cm and the reference recording electrodes over the thumb and little finger, respectively; and (3) antidromic median digital sensory studies of the index finger with ring electrodes at 13 cm. Sensory nerve action potentials were recorded with filter settings of 20 Hz and 2 KHz, a sweep speed of 2 msec per division, and a sensitivity of 20 μ V per division. Latency was measured to the negative peak, and amplitude was measured from baseline to peak. Compound muscle action potentials were recorded with filter settings of 2 Hz and 10 KHz, a sweep speed of 5 msec per division, and a sensitivity of 5 mV per division for determination of amplitude and a sensitivity of 500 μ V per division for the determination of latency. Latency was measured to the onset of the negative peak, and amplitude was measured from baseline to peak. The electrophysiological parameters are listed in Table I. All studies were performed by physicians experienced on a TECA TD-5 electromyograph (TECA Corp., Pleasantville, N.Y.). The machine was calibrated each day before testing. Hand temperature was not measured prior to NCS since it was already measured prior to administering the Wisconsin test battery.

Category Assignment

All of the experimenters were blind to subject medical records and the outcomes from the other evaluations (physical examination, NCS, and Wisconsin CTS tests). Results of the medical and electrodiagnostic evaluation were separately reviewed, and the final determination of the presence or absence of CTS symptoms, as well as the existence of positive NCS results for each hand, was made independently. The NCS⁻ condition was defined as no electrodiagnostic evidence of median mononeuropathy at the carpal tunnel. The criteria for NCS⁻ were median motor latency less than or equal to 4.5 msec at 8 cm, median sensory latency less than or equal to 3.7 msec at 13 cm, and a difference between median and ulnar transcarpal latencies less than 0.5 msec.⁽¹⁸⁾ NCS⁺ was defined as electrodiagnostic evidence of median mononeuropathy. The judgment of NCS⁺ was not dependent on all of the NCS⁻ criteria. Hands showing positive results in some NCS parameters and negative results in others were judged NCS⁺. Symptom⁻ was applied to hands with no CTS-related symptoms based on examination and questionnaire responses. Symptom⁺ was applied to hands with symptoms compatible with CTS. The distribution of the hand categorization for all subjects is provided in Table II.

Wisconsin CTS Test Battery

The test battery consisted of two functional sensory and psychomotor tests. An automated aesthesiometer was used to measure tactile sensitivity while the finger freely probed a tiny gap on an otherwise smooth surface.⁽¹⁰⁾ Hand sensory thresholds were measured as the minimum gap width needed for detecting a gap on a smooth surface. Gap size was changed using a micropositioner and digital encoder. Gap displacement, speed, and direction were controlled by a microcomputer. As the gap size was changed, subjects repeatedly responded verbally to communicate whether they could

TABLE I. Electrophysiological Parameters on Median and Ulnar Nerves and Their Notations

Electrophysiological Parameters	Notation	Measurement	Unit
Median nerve			
Sensory latency	L _{MS}	evoked by antidromic stimulation of the index finger at 13 cm	msec
Sensory amplitude	A _{MS}	evoked by antidromic stimulation of the index finger at 13 cm	μ V
Motor latency	L _{MM}	stimulation above wrist with 8 cm conduction distance	msec
Motor amplitude	A _{MM}	stimulation above wrist with 8 cm conduction distance	mV
Transcarpal latency	L _{MT}	palm stimulation with 8 cm ^A conduction distance	msec
Transcarpal amplitude	A _{MT}	palm stimulation with 8 cm ^A conduction distance	μ V
Ulnar nerve			
Motor latency	L _{UM}	stimulation above wrist with 8 cm conduction distance	msec
Motor amplitude	A _{UM}	stimulation above wrist with 8 cm conduction distance	mV
Transcarpal latency	L _{UT}	palm stimulation with 8 cm ^A conduction distance	msec
Transcarpal amplitude	A _{UT}	palm stimulation with 8 cm ^A conduction distance	μ V
Difference between median and ulnar transcarpal latency	Δ L _{MUT}	palm stimulation with 8 cm ^A conduction distance	msec

Note: Latency parameters were measured from the onset of the motor action potential and the negative peak of the sensory action potential.

^AA 10-cm transcarpal electrode separation distance was used for some large hands, and NCS outcomes were interpreted based on that separation. Those data were excluded from the correlation analysis.

detect a gap using the converging staircase method of limits paradigm.⁽¹²⁾ The gap detection test controlled contact force at 50 g.

The rapid pinch and release psychomotor test⁽¹¹⁾ measured performance in terms of speed and force control. An aluminum strain

TABLE II. Hand Distribution in the Symptom $\times$ NCS Categories

CTS symptoms	Median Nerve NCS	
	-	+
-	23 hands (from 16 subjects) ^A	6 hands (from 5 subjects)
+	14 hands (from 11 subjects)	11 hands (from 9 subjects)

^AEach hand was categorized into one unique cell. The number in parentheses shows the corresponding number of subjects.

gauge dynamometer⁽¹⁹⁾ was pinched using the index finger and thumb. A pulp pinch strength test was administered for determining the maximal voluntary contraction (MVC) using the greater of two exertions. The objective of the pinch and release psychomotor test was to pinch the dynamometer above an upper force level (F_{UPPER}) and then release below a lower force level (F_{LOWER}) as quickly as possible. Performance measures for this test were averaged over all successful pinch exertions in 5 seconds. All force measurements were normalized by expressing force in terms of percentage MVC. These measures and their notation are listed in Table III. Subjects performed the test using alternate hands and completed four conditions of F_{UPPER} (5, 20, 35, and 50 %MVC) for each hand. F_{LOWER} was fixed at 2 %MVC. As suggested by a previous study,⁽¹³⁾ comparisons between subjects were made using F_{UPPER} of 20 %MVC.

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

Variable	Notation	Units
Pinch rate	R_p	pinches/sec
Change in pinch rate with respect to F_{UPPER}	$R_p/\Delta F_{UPPER}$	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

The gap detection sensory test was administered first, followed by the rapid pinch and release psychomotor test. Subjects were provided with practice in the sensory test including a variety of gap widths. Both hands of all subjects were tested. Half of the subjects performed the test using the dominant hand first; the other half used the nondominant hand first. A short rest period was provided after subjects finished the gap detection sensory test. The psychomotor pinch test began with a practice set. Subjects were allowed to practice as long as desired prior to the beginning of every new trial.

Statistical Analysis

The experiment was a repeated measures full factorial design using the hand as a random effect variable nested within group and using age as a covariate. Pearson product correlation was used to find the relationship between the functional test variables and electrophysiological parameters. Analysis of variance using age as a covariate was performed separately for each performance variable of the gap detection test and the rapid pinch and release test. Hands were *a priori* classified as Symptom⁺/Symptom⁻ or NCS⁺/NCS⁻ according to medical evaluations and NCS. Stepwise discriminant analysis was performed to determine the combination of test variables that best predicted the group to which a case belonged.

RESULTS

Two-way analysis of variance, using age as a covariate, was used for evaluating the functional performance variables according to symptom and median nerve electrodiagnostic evaluation. Hands were treated as individual members in all statistical analyses. Age was not a significant covariate for any of the functional test variables ($p > .1$). Gap detection sensory thresholds were significantly different between the NCS⁻ and NCS⁺ categories. The average gap detection sensory threshold (mean = 0.25 mm, standard deviation [SD] = 0.07) was 32% greater for the NCS⁺ category compared with the NCS⁻ category (mean = 0.19 mm, SD = 0.06). The average gap detection sensory threshold was not significantly different between the Symptom⁺ and the Symptom⁻ hands ($p > .1$). There were significant differences between NCS⁺ and NCS⁻ categories and between Symptom⁺ and Symptom⁻ categories for $\Delta R_p/\Delta F_{UPPER}$, T_{LOWER} , and pinch strength (see Table IV). Hands lacking CTS symptoms had a significantly greater R_p but lower F_{OVER} than hands with CTS symptoms ($p < .05$).

The Tukey studentized range test was performed for significant variables. In general, hands in the NCS⁻ categories performed better than hands in the NCS⁺ categories for most of the functional test variables (see Table IV). The Symptom⁻/NCS⁺ group had an average pinch strength of 66.5 N, which was significantly greater than that of the other groups ($p < .05$). There were only six hands in the Symptom⁻/NCS⁺ group, and three hands (two subjects) had the greatest pinch strength among the entire studied sample. No pinch strength differences were observed among the other groups.

Pearson product correlation coefficients were obtained between electrodiagnostic parameters and functional test variables (see Table V). Since the majority of median and ulnar transcarpal latencies were measured at 8 cm, data for the transcarpal latencies measured for 10 cm (8 out of 54 hands) were excluded from the correlation analysis. In general, there were significant ($p < .01$) correlations between median nerve latencies and functional test variables ($0.3 < r < 0.6$). Significant ($p < .01$) correlations between median nerve latencies and pinch strength were also observed ($0.4 < r < 0.5$).

Stepwise discriminant analysis was performed to determine the combination of Wisconsin test variables that would best classify the four categories, including Symptom⁻/NCS⁻, Symptom⁻/NCS⁺, Symptom⁺/NCS⁻, and Symptom⁺/NCS⁺. Different category combinations were applied to dichotomize subjects for investigating the use of the functional tests that best differentiated positive cases from negative cases according to different criteria (see Table VI). All gap detection sensory threshold and psychomotor test variables were initially included in the analysis. Forward selection was applied. Variables were entered if the F statistic was greater than 4.00 ($p < 0.05$ for a sample size of 60 observations), and removed if the F statistic was less than 3.996. The F-to-enter variables not in the current equation were computed using a one-way analysis of variance where the covariates were the variables in the current equation. Several criteria were explored to find the canonical variables that best differentiated the two groups. Differentiation between the Symptom⁻/NCS⁺, Symptom⁺/NCS⁻, and Symptom⁺/NCS⁺ groups and the Symptom⁻/NCS⁻ group selected $\Delta R_p/\Delta F_{UPPER}$ into the discriminant function, which had a sensitivity of 0.74 and specificity of 0.83 (see Table VI). The discriminant function correctly assigned 23 out of 31 hands of the positive cases into their correspondent category and 19 out of 23 hands of the negatives into their correspondent category.

A receiver operating characteristic (ROC) curve was constructed using the canonical variables for differentiating

TABLE IV. Means and Standard Deviation (in Parentheses) for the Functional Performance Variables Between Four Subject Categories

	Symptom ⁻ NCS ⁻	Symptom ⁺ NCS ⁻	Symptom ⁻ NCS ⁺	Symptom ⁺ NCS ⁺	F Value ^A
Number of hands	23	14	6	11	
Gap detection threshold (mm)	0.18 (0.05)	0.20 (0.07)	0.23 (0.04)	0.27 (0.08)	4.85 ^B
Pinch rate (pinches/sec)	4.8 (0.8)	4.3 (0.8)	4.7 (0.6)	3.5 (0.5)	7.58 ^C
Pinch rate change with respect to change in force (pinches/sec/%MVC)	-0.050 (0.013)	-0.035 (0.016)	-0.032 (0.014)	-0.023 (0.011)	10.36 ^C
Overshoot force (%MVC)	14.9 (7.0)	20.8 (11.4)	19.5 (6.2)	24.7 (8.0)	3.69 ^D
Time above the upper force level (msec)	83.4 (18.5)	95.3 (30.2)	103.9 (21.1)	101.2 (17.9)	2.44
Time below the lower force level (msec)	54.3 (14.0)	61.2 (14.1)	61.0 (12.1)	74.2 (10.4)	5.65 ^B
Pinch strength (N)	43.9 (13.4)	42.1 (8.8)	66.5 (28.0)	47.7 (17.9)	3.92 ^D

^AF statistics were calculated using one-way analysis of variance treating subject categories as the independent variable.

^Bp<.01

^Cp<.001

^Dp<.05

Symptom⁺/NCS⁺ hands from hands in other categories (see Figure 1). The binormal ROC curve was fitted using a maximum likelihood estimation on the categories denoted 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. The estimated area beneath the fitted ROC curve was 0.89 with a standard deviation of 0.05.

results were consistent with previous findings.^(9,13) The correlation coefficients between the NCS median nerve latencies and the functional performance variables were less in the current study ($0.3 < r < 0.6$) than in previous investigations ($0.5 < r < 0.8$). This was possibly because previous studies selected only well-defined CTS cases and control subjects, resulting in a bimodal distribution that enhanced the correlations. In the current study the distribution of cases was less dichotomous and more uniform.

TABLE V. Correlation Coefficients and Statistical Significance Levels for the Electrophysiological Parameters and Functional Performance Variables

	Median Nerve Latencies			Ulnar Nerve Latencies	
	L _{MS}	L _{MM}	L _{MT}	L _{UM}	L _{UT}
Number of hands	54	54	46	54	46
Gap detection threshold	0.583 ^A	0.552 ^A	0.507 ^A	0.356 ^B	0.201
Pinch rate	-0.452 ^A	-0.357 ^B	-0.446 ^B	-0.135	-0.307 ^C
Change in pinch rate	-0.571 ^A	-0.410 ^B	-0.507 ^A	0.104	0.316 ^C
Overshoot force	0.379 ^B	0.278 ^B	0.270	0.175	0.233
Time above F _{UPPER}	0.327 ^C	0.345 ^C	0.310 ^C	0.099	0.047
Time below F _{LOWER}	0.580 ^A	0.486 ^A	0.455 ^B	0.300 ^C	0.373 ^C
Pinch strength	0.530 ^A	0.403 ^B	0.410 ^B	0.275 ^C	0.360 ^C

Note: Hands included in the correlation analysis were measured at 8 cm for L_{MT} and L_{UT}. Hands measured at 10 cm were excluded from the correlation analysis.

^Ap<.001

^Bp<.01

^Cp<.05

DISCUSSION

Of all the functional performance variables, the gap detection sensory threshold was significantly impaired for NCS⁺ hands relative to NCS⁻ hands (see Table IV). There was no difference, however, in gap detection threshold between Symptom⁺ and Symptom⁻ hands. These results indicate that the Wisconsin sensory test performance was related to electrophysiological parameters regardless of symptoms. The psychomotor variables $\Delta R_p/\Delta F_{UPPER}$ and T_{LOWER} were significantly different between the Symptom⁺ and Symptom⁻ groups and between the NCS⁺ and NCS⁻ groups. The variables R_p and F_{OVER} differed according to CTS symptoms, but not according to NCS findings.

Good correlations were observed between the median nerve distal sensory, distal motor, and transcarpal latencies and the functional performance variables for all hands pooled together. The

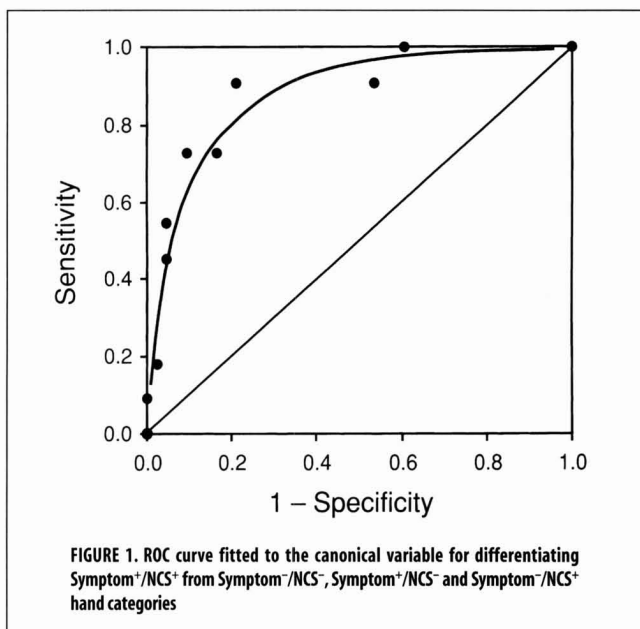
Although pinch strength differed with CTS symptoms and NCS findings, it was likely because of the small number of subjects (six hands) in the Symptom⁻/NCS⁺ category, in which three out of four hands had the greatest pinch strength among the entire 54-hand sample. Results of high pinch strength in the Symptom⁻/NCS⁺ category caused the symptom, NCS, and the Symptom $\times$ NCS interaction effects to be significant for pinch strength. It also resulted in a much larger pinch strength for the NCS⁺ categories than for the NCS⁻ categories. No physiological or electrophysiological rationale would suggest that hands having median nerve entrapment have greater pinch strength than hands without median nerve entrapment. In fact, weakness usually occurs in severe

TABLE VI. Sensitivity and Specificity of Functional Performance Variables

Case Definition (Symptoms, NCS)				Canonical Variable ^B	Sensitivity	Specificity
(-, -) ^A	(-, +)	(+, -)	(+, +)			
Canonical variables from stepwise discriminant analysis						
Neg. pos.	pos.	pos.	pos.	$2.77+71.81\times\Delta R_p/\Delta F_{UPPER}$	0.74	0.83
Neg. neg.	pos.	pos.	pos.	$2.59+67.22\times\Delta R_p/\Delta F_{UPPER}$	0.72	0.76
Neg. pos.	neg.	pos.	pos.	$2.61+67.56\times\Delta R_p/\Delta F_{UPPER}$	0.71	0.68
Neg. neg.	neg.	pos.	pos.	$5.92-1.35\times R_p$	0.82	0.81
Neg. N/AC	N/A	pos.	pos.	$0.93+8.29\times\text{Threshold}+65.00\times\Delta R_p/\Delta F_{UPPER}$	0.91	0.87
Current data applied to the canonical variables established from the previous study						
Neg. pos.	pos.	pos.	pos.	$-1.07+32.23\times\Delta R_p/\Delta F_{UPPER}+0.04\times T_{LOWER}$	0.71	0.74
Neg. neg.	pos.	pos.	pos.	$-1.07+32.23\times\Delta R_p/\Delta F_{UPPER}+0.04\times T_{LOWER}$	0.72	0.66
Neg. pos.	neg.	pos.	pos.	$-1.07+32.23\times\Delta R_p/\Delta F_{UPPER}+0.04\times T_{LOWER}$	0.82	0.62
Neg. neg.	neg.	pos.	pos.	$-1.07+32.23\times\Delta R_p/\Delta F_{UPPER}+0.04\times T_{LOWER}$	0.91	0.58
Neg. N/A ^C	N/A	pos.	pos.	$-1.07+32.23\times\Delta R_p/\Delta F_{UPPER}+0.04\times T_{LOWER}$	0.91	0.74

^A+ = positive symptoms NCS, - = negative symptoms or negative NCS.
^BCase positive when canonical variable > 0, case negative when canonical variable <=0.
^CN/A = not applicable

cases of median nerve entrapment as a result of thenar muscle atrophy.⁽²⁰⁻²³⁾ This implies that strength was not a good indicator of NCS. All other categories had equivalent pinch strength except



the Symptom⁻/NCS⁺ category, indicating that the results of the comparison between the NCS⁺ and NCS⁻ categories were not biased by extreme cases of late-stage CTS subjects. Pinch strength was normalized in the psychomotor performance variables by measuring pinch force relative to MVC.

Stepwise discriminant analysis was an iterative stepwise approach for selecting the best combination of functional test variables that differentiate Symptom⁻/NCS⁻ from the other categories (see Table VI). Using *a priori* criteria, the only performance variable that was accepted as a canonical variable was $\Delta R_p / \Delta F_{UPPER}$. Additional Wisconsin test variables not selected into the discriminant function could have been excluded because of the high correlation between $\Delta R_p / \Delta F_{UPPER}$ and other variables. Consequently, after $\Delta R_p / \Delta F_{UPPER}$ was entered into the discriminant function, the contribution from the other variables was accounted for. The ratio $\Delta R_p / \Delta F_{UPPER}$ was also selected as the canonical variable for differentiating NCS⁺ hands from NCS⁻ hands, with a 0.71 sensitivity and 0.68 specificity. Pinch rate differentiated Symptom⁺/NCS⁺ hands from hands in the other three categories with a 0.82 sensitivity and 0.81 specificity. The canonical variable used to separate Symptom⁺/NCS⁺ hands from Symptom⁻/NCS⁻ hands had a 0.91 sensitivity and 0.87 specificity. The differentiation, however, used only the hands from the Symptom⁻/NCS⁻ and Symptom⁺/NCS⁺ categories and excluded data from the Symptom⁻/NCS⁺ and Symptom⁺/NCS⁻ categories. This category selection was used for comparing the results with the previous study that used similar subject category criteria.

The ROC curve and the area under the ROC curve indicated that the canonical variables had similar capability for separating Symptom⁻/NCS⁻ from the other categories as the canonical variables determined for a bimodally distributed population.⁽¹³⁾ The different functional test parameters used in canonical variables for the current and previous studies might reflect correlations between these functional performance variables. Selecting different functional performance variables for the canonical variables resulted in only a slight change to the sensitivity and specificity.

The sensitivity and specificity using the discriminant function derived from the previous study⁽¹³⁾ for the current data is listed in Table VI. A ROC curve fitting the current data to the previously established discriminant function showed that the area under the ROC curve was 0.85 with an SD of 0.05. The functional test variables used in the current canonical variables were the gap detection threshold and $\Delta R_p / \Delta F_{UPPER}$, while the previous canonical variables were $\Delta R_p / \Delta F_{UPPER}$ and T_{LOWER} .

Two ROC curves were obtained using the current data fitted into the two different canonical variables derived from the stepwise discriminant analysis for differentiating Symptom⁻/NCS⁻ hands from the other categories and the canonical variable from the previous study⁽¹³⁾ for differentiating normal subjects from positive cases. Symptom⁺/NCS⁻, Symptom⁻/NCS⁺, and Symptom⁺/NCS⁺ subjects from the current study were considered positive cases for this comparison. A univariate z-score test for comparing the areas under these two ROC curves was performed. The z score for the computed correlated area test was 0.844 ($p > .1$), showing no significant difference between the ROC curves using the current canonical variable and the one obtained by fitting the current data into the previously established discriminant function. The results indicated that there was no significant difference between using the gap detection threshold and $\Delta R_p / \Delta F_{UPPER}$, or $\Delta R_p / \Delta F_{UPPER}$ and T_{LOWER} , which was included in the previous canonical variable, in terms of sensitivity and specificity for differentiating Symptom⁺/NCS⁺ hands from hands in the other categories. It also suggests that hands in the Symptom⁻/NCS⁻, Symptom⁺/NCS⁻,

and Symptom⁻/NCS⁺ would have had high chance of being predicted as negative cases using the previously established canonical variable. Based on the results from this study, the functional test battery had a fairly good sensitivity and specificity for differentiating positive cases from negative cases in the study population.

Median nerve latency means were not significantly different between normal subjects in the current and previous studies.^(11,13) CTS patients in the previous study had slightly longer average median nerve latencies (though not statistically significant) than the current study involving industrial workers. Normal subjects' results for all of the functional performance test variables were very similar to those found previously. In general, Symptom⁺/NCS⁺ cases in the current study had slightly better performance than the CTS patients in the previous study. The subjects were similar in average age between the two studies, although the CTS group for the previous study had a wider age range (between 23 and 79 years old) than for the current study (between 30 and 54 years old).

Stepwise discriminant analysis was used as an objective procedure for selecting the Wisconsin test variables that best differentiated positive cases from negative cases in both the previous CTS-normal study⁽¹³⁾ and the current study. The previous study selected $\Delta R_p/\Delta F_{UPPER}$ and T_{LOWER} for the optimal discriminant function, which are both from the psychomotor pinch test. The use of the gap detection test in the previous study was unclear. Stepwise discriminant analysis in the current study selected the psychomotor variable $\Delta R_p/\Delta F_{UPPER}$ and the gap detection threshold for canonical variables to differentiate Symptom⁻/NCS⁻ hands from Symptom⁺/NCS⁺ hands. The differences in the canonical variables very likely reflect the different subject selection criteria between these two studies.

It was anticipated that two hands from an individual subject may have different outcomes from the NCS and symptoms evaluation. Two alternative approaches were considered for dealing with the apparent categorization problem. The first was to study only one hand from each subject. This was not feasible because of the low prevalence of CTS and the small sample size available. The alternative approach was to treat each hand as an individual subject. This approach violated the assumption of subject independence since the two hands from the same subject may have significant correlation in many aspects. Treating each hand as a subject increased the degrees of freedom for statistical analyses. The latter approach was adopted for practical considerations. The magnitude of differences observed suggests that the results were robust despite the potential hand correlation bias.

Data were analyzed separately for both dominant and nondominant hands. There were 7, 11, 4, and 5 dominant hands assigned to the Symptom⁻/NCS⁻, Symptom⁺/NCS⁻, Symptom⁻/NCS⁺, and Symptom⁺/NCS⁺ categories, respectively. In the same way, 16, 3, 2, and 6 nondominant hands were respectively assigned into the four categories. Due to the small sample size, the analyses using dominant and nondominant hand data separately should be regarded as tentative. This is particularly important for the nondominant hand data because of the unbalanced sample sizes among the four categories. There were significant differences among the four categories for the gap detection threshold ($F(3,22) = 3.76, p < .05$), pinch rate ($F(3,22) = 3.87, p < .05$), pinch rate change to the upper force level ($F(3,22) = 3.21, p < .05$), and time below the lower force level ($F(3,22) = 3.04, p < .05$) for the dominant hand. In general, hands in the Symptom⁻/NCS⁻ had the best functional performance and hands in the Symptom⁺/NCS⁻ performed the worst. No significant differences were observed for overshoot force, time above the upper force level, or hand pinch strength among the four categories.

Significant differences were observed among the four hand categories for pinch rate ($F(3,22) = 3.38, p < .05$), pinch rate change to the upper force level ($F(3,22) = 7.83, p < .001$), and overshoot force ($F(3,22) = 7.32, p < .001$) for the nondominant hand data. Symptom⁻/NCS⁻ hands had the best performance and Symptom⁺/NCS⁻ hands performed the worst, similar to the dominant hand. No significant differences among the four categories were observed for other functional test variables when separating dominant from nondominant hands. In summary, the hand-separated data analyses were similar to the hand-mixed data analyses. The correlation analysis also showed similar trends between the hand-separate data sets and the hand-mixed data set.

A previous study involving CTS patients and normal subjects suggested that the Wisconsin functional psychomotor and sensory tests might be considered for monitoring CTS in the workplace.⁽¹³⁾ Although it was an important preliminary investigation, that study was spectrum biased since it involved only two extremes: confirmed CTS cases were compared with normal subjects free of CTS. The proportion of operators in the selected worker sample was 46% with CTS Symptom⁺ and 31% with NCS⁺. The proportion of Symptom⁺ or NCS⁺ subjects was 57%, and CTS Symptom⁺/NCS⁺ was 20%. Consequently, the selection procedure for the current study achieved a wide case distribution using a fairly small sample. The distribution of subjects in this study with respect to symptoms and NCS parameters may not be representative of any given industrial population. The rationale for the subject selection procedure employed was to test the Wisconsin test battery using a subject distribution that was less likely to exaggerate differences than the bimodal distribution used previously.^(11,13)

The major limitations of this study are the relatively small sample size ($N = 54$ hands) and nonrandom sampling approach. The outcome was consequently sensitive to misclassification. Longitudinal studies are now being performed incorporating larger random samples as an outcome of this study. Future work will also investigate potential confounding effects of other musculoskeletal disorders and the utility of using both sensory and psychomotor tests for differentiating CTS from other work-related cumulative trauma disorders. It is anticipated that the sensory test could serve to differentiate between CTS and non-CTS cases.

The Wisconsin CTS test battery is noninvasive and suitable for routine testing. The results of this investigation found that the Wisconsin CTS sensory test corresponded with NCS parameters, regardless of symptoms. The psychomotor test performance was affected by both the presence of symptoms and electrophysiological deficits. These outcomes suggest that such a test may be useful for objectively monitoring workers for potential CTS symptoms and nerve conduction deficits in injury surveillance and epidemiological investigations. Furthermore, this study has shown that the Wisconsin CTS test battery can differentiate individuals with CTS symptoms combined with NCS parameters consistent with CTS from others, and the study allows new understanding about functional deficits associated with CTS symptoms and NCS.

CONCLUSIONS

Results of this study indicated that hands in the Symptom⁻/NCS⁻ category had significantly better functional test performance than hands in the Symptom⁺/NCS⁺ category for most of the test variables. There was a significant gap detection threshold difference between NCS⁺ hands and NCS⁻ hands. If the criterion was set to separate Symptom⁺/NCS⁺ hands from hands in all other categories, the pinch rate had a sensitivity of 0.82 and specificity of 0.81.

Pinch rate change with respect to the upper force level, $\Delta R_p / \Delta F_{\text{UPPER}}$, was selected for differentiating NCS⁺ hands and NCS⁻ hands. Use of the gap detection threshold and $\Delta R_p / \Delta F_{\text{UPPER}}$ could best differentiate Symptom⁺/NCS⁺ cases from Symptom⁻/NCS⁻ cases. The sensitivity was 0.91 and specificity was 0.87.

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