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Innovative Quantitative Assessment of Hand Function in Carpal Tunnel Syndrome

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Abstract

Background: Carpal tunnel syndrome (CTS) compromises fine sensorimotor function during activities of daily living and affects a large number of individuals with high burden costs for society. The purpose of this study was to quantitatively characterize fine movement skills in CTS patients preoperatively and at 1 month postoperatively by means of a sensor-engineered glove, in order to provide new insights for evaluative and finally therapeutic purposes. **Methods:** Forty-one CTS patients and 41 age- and gender-matched healthy controls (HC) were analyzed by adopting the engineered glove Hand Test System (HTS), which previously demonstrated its reliability and sensitivity to detect hands dysfunction in several neurological diseases. A sub-group of 11 CTS subjects was re-tested 1 month after surgery. Three parameters—touch duration (TD), inter-tapping interval (ITI), and movement rate (MR)—were considered to characterize hand function. **Results:** The affected hand of CTS patients generally showed worst finger opposition performances than HC. Comparing the dominant hand, all parameters were able to significantly discriminate CTS patients from HC. Considering the nondominant hand, the best performing parameter in discriminating CTS from HC was TD. The follow-up assessment at 1 month after surgery showed that considered parameters were able to monitor patients' recovery. In particular, the TD parameter recorded at the 3 different assigned task modalities resulted significantly enhanced. **Conclusions:** Results of this pilot study proved the validity of the parameters obtained through the sensor-engineered glove to assess objectively hand functional status and surgical outcomes in CTS.

Keywords: carpal tunnel syndrome, nerve, diagnosis, hand function, outcome measures, sensor engineered glove, quantitative, assessment

Introduction

Carpal tunnel syndrome (CTS) is an entrapment neuropathy of the median nerve at the wrist with an incidence of 329 cases per 100,000 person/year.[1] It has a prevalence of approximately 3% in the general population and nearly 8% in the working population.[2,3] It may occur as a work-related disorder, with a 5-fold higher incidence in workers exposed to repetitive motion.[4]

Carpal tunnel syndrome (CTS) severely impacts the daily life of patients, impairing their autonomy and causing inability to work.[5] During activities of daily living, patients with CTS often experience unintentional dropping of objects and grip inaccuracy. Symptoms include neuropathic pain, paraesthesia, dysaesthesia, and functional motor impairment that leads to inabilities in performing fine motor tasks which involve the thumb and index fingers. This compromises the ability to execute activities of daily living such as fine manipulation, writing, using utensils, thus reducing the quality of life.

Identifying and quantifying CTS motor deficits are crucial for enhancing diagnostic procedures and therapeutic treatments. Currently, CTS is a clinical diagnosis. The diagnosis is suspected when the characteristic symptoms and signs are present. The hallmarks of CTS are pain and paresthesias in the distribution of the median nerve, which includes the palmar aspect of the thumb, index and middle fingers, and radial half of the ring finger. Nonetheless, their absence does not rule out the diagnosis of CTS. Provocative maneuvers (e.g. Phalen, Tinel, manual carpal compression, and hand elevation tests) are helpful but their diagnostic accuracy for CTS varies widely and their sensitivity and

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specificity in CTS isolation is moderate at best.[6-11] Moreover, most patients with early, mild to moderate CTS cannot have physical examination findings. The electrodiagnostic studies aid in confirming the diagnosis in atypical cases, determining severity, and planning surgery. Electrodiagnostic studies have a sensitivity of 56% to 85% and specificity of 94% to 99% for CTS.[12] Results may be normal in up to one-third of patients with mild CTS.[13] Such methods usually indicate abnormalities in patients with advanced CTS, and result to not be sensitive enough to detect motor function abnormalities at early stages of disease.

Recently, advanced motion analysis methods showed the potential to identify subtle kinematic changes associated with pathological hand conditions that are undetectable using traditional approaches. Such sophisticated approaches based on capture motion analysis were able to highlight kinematic dyscoordination movements due to CTS-associated alterations in sensorimotor function.[14-16] In particular, kinematic analysis of tasks requiring thumb opposition movements showed to address significant insights about hand function impairment associated with CTS given the critical role of the thumb in dexterous manipulation.[17] Characterizing movement features with advanced assessment methods may provide further insight into functional consequences, and guide considerations for CTS diagnosis and treatment. Nevertheless, these methods for accurate capture of 3-dimensional human movement require a laboratory equipment and, generally, markers attached to the body's segments, thus resulting in a complex, time-consuming approach, inadequate for clinical exploitation.

The purpose of this study was to evaluate hand motor deficit and postsurgery recovery of CTS individuals by adopting an objective and cost-effective device based on a sensor-engineered glove. Its sensitivity was already reported in different applications in which the sensor-engineered glove was able to detect subclinical impairment otherwise unveiled by the commonly adopted clinical scales.[18-20]

Methods

Participants

Forty-one individuals with CTS and 41 healthy volunteers (ie, the healthy control [HC] group) were evaluated in this study, preserving age and gender ranges across the 2 sets. Subjects with CTS, recruited at Hand Surgery Unit of Cittadella Socio Sanitaria di Cavarzere (Cavarzere, Italy), had moderate or severe suffering at median nerve without showing motor deficits and were diagnosed according to the clinical and electrophysiological findings. All the evaluated subjects presented moderate or severe CTS according to electrophysiological classification of the severity described by Padua et al.[21] In order to avoid the effect of concurrent pathologies, subjects with arthritis, stenosing tenosynovitis, De Quervain's tenosynovitis, previous trauma, and injury, were excluded. With the hypothesis that CTS would lead to reduced performance in finger opposition movements, fine movement skills were compared between affected individuals and healthy controls (HC). Patients were evaluated at the affected upper extremity (dominant or nondominant hand) just before surgery. Hand function of a subgroup of 11 CTS subjects was re-tested at 1 month after the surgery treatment of median nerve decompression. The HC group was evaluated at dominant and nondominant hand, as verified by the Edinburgh Handedness Inventory.[22] Patient informed consent was obtained according to institution policy and the declaration of Helsinki.

Experimental Procedures

The Hand Test System (HTS), a sensor-engineered glove produced by ETT S.p.A (Genoa, Italy), was adopted to evaluate finger opposition movements in a quantitative spatial-temporal way. The HTS was used according to previously published protocols.[23,24] Briefly, the device is based on a pair of engineered silk gloves connected to a notebook equipped with a software that allows to acquire data and obtain the automatic analysis of specific parameters. Subjects were instructed to wear the gloves and execute repetitively the "index-medium-ring-little (IMRL) sequence" (consisting in the opposition of thumb to index, medium ring, and little fingers) in 3 different modalities: spontaneous velocity, maximum velocity and metronome rhythm (paced at 2 Hz). Each task took 60 seconds adopting the "eyes-closed paradigm," to avoid possible confounding effects due to integration of acoustic and visual information. Among the parameters processed by the software included in the system (HTS, Software Version 1.0.0) the following were selected: touch duration (TD), which is the contact time between thumb and another finger (in ms); inter-tapping interval (ITI), which represents the time between the end of the contact of the thumb and another finger and the beginning of successive contact (in ms); movement rate (MR), which is the frequency of complete motor task, computed as 1/ (TD + ITI) (in Hz).

Statistical Analysis

Subjects were age- and gender-matched for hand dominance. The distribution of the data was tested for normality using a quantile-quantile (Q-Q) plot. A nonparametric analysis was also carried out to assess the group differences mitigating the possible effects of outliers. The Mann-Whitney-Wilcoxon Test was performed to compare fine movement skills between CTS and HC group; the Wilcoxon signed-rank test was performed to compare the hand performance of individuals with CTS pre- and postsurgery treatment. For statistical comparisons, a P-value lower than .05 was considered significant. Statistical analyses

Table 1. Subjects Hand Performance Evaluated by the Means of the Sensor Engineered Glove.

Parameters	HC (N = 41)	CTS (N = 41)
Spontaneous velocity		
TD (ms)	305.93 ± 21.23	401.93 ± 21.49 (**)
ITI (ms)	234.05 ± 17.04	266.98 ± 16.19 (*)
MR (Hz)	2.00 ± 0.11	1.58 ± 0.08 (**)
Maximum velocity		
TD (ms)	229.51 ± 15.58	298.09 ± 17.09 (**)
ITI (ms)	155.85 ± 11.33	188.85 ± 11.66 (*)
MR (Hz)	2.80 ± 0.15	2.22 ± 0.09 (**)
2 Hz Metronome		
TD (ms)	260.64 ± 14.54	282.30 ± 11.78 (*)
ITI (ms)	252.06 ± 8.97	224.61 ± 11.43 (ns)
MR (Hz)	2.00 ± 0.04	2.02 ± 0.04 (ns)

Note. In the table are reported the hand performance of HC and CTS subjects at spontaneous velocity, maximum velocity, 2 Hz metronome modality. The mean ± SE values are reported for considered parameters: TD (touch duration), ITI (inter-tapping interval) and MR (movement rate). Significant differences between HC and CTS groups are reported (**$P < .01$; *$P < .05$). HC = healthy controls; CTS = carpal tunnel syndrome.

were performed using the R software/environment (Foundation for Statistical Computing, Vienna, Austria).

Results

Table 1 reports subjects' fine movement characteristics provided by the sensor-engineered glove HTS. A total of 42 subjects (21 HC and 21 CTS) were analyzed at dominant hand, while 40 subjects (20 HC and 20 CTS) were analyzed at nondominant hand. The Table 2 reports subjects' dominant and nondominant hand performance provided by the sensor-engineered glove system. Considering the dominant hand, all the parameters evaluated at spontaneous velocity and at maximum velocity mode resulted to differ significantly between CTS and HC groups (Figure 1). In particular, for both protocols, groups comparison resulted in $P < .01$ for TD and ITI, and $P < .05$ for MR. Comparing groups at nondominant hand, the TD parameter obtained at spontaneous velocity and the TD and MR parameters retrieved at maximum velocity resulted significantly different, showing $P < .05$. The task relying on metronome paced at 2 Hz at both hands (dominant and nondominant) did not show significant differences between the 2 groups (Figure 1).

The follow-up assessment was conducted on a subset of CTS group composed by 11 individuals (6 females and 5 males with age ranging from 48 to 67 years) 1 month after the surgical treatment. CTS hand performance before and after the intervention is reported in Table 3. CTS group generally showed a better hand performance after treatment. The TD parameter recorded at each velocity mode (spontaneous velocity, maximum velocity, metronome paced at 2 Hz) significantly improved in CTS at re-test analysis: comparison of the distributions resulted in $P < .01$, for each condition. Interestingly, the hand performance of individuals with CTS 1 month after surgery (Table 3) did not show significant differences when compared with the performance of the HC group (see Table 1).

Discussion

Symptoms of CTS often impair motor function during daily activities. Currently, the accepted methods for CTS diagnosis and follow-up are based on clinical evaluation of its sensory and motor manifestations and patient-reported outcome. Even when traditional measurements such as pinch strength do not indicate weakness, deficient motor capabilities may be present and interfere with successful completion of dexterous tasks. Electrodiagnostic testing is a powerful tool for diagnosis of CTS. Nonetheless it has a considerable associated cost and the procedure itself is uncomfortable for patients. An objective measurement of hand motor function can assist enhancing diagnosis procedures and evaluating the effectiveness of potential treatments. To this purpose, a sensor-engineered glove (HTS) was exploited to measure hand dexterity by analyzing kinematic parameters during finger opposition movements. To avoid detecting the effect of concurrent pathologies, we excluded subjects with arthrosis, stenosing tenosynovitis, De Quervain's tenosynovitis, previous traumas and injuries. We did not exclude patients with diabetes mellitus and thyroid function, well-known risk factors for CTS that can affect the precision grip and lead to a relevant decline in grip strength, respectively.[25,26] The reason was that in our protocol the patient executed 3 60-second tasks that could be carried out easily without causing fatigue during the exercise. Moreover, the results are based on the capability of the subject to perform the opposition of thumb to index, medium ring, and little fingers that involves not only fine motor strength but also fine motor precision. In this condition, we assume that these pathologies are not able to affect hand motor performance in our test. In previous studies, the sensor-engineered glove showed to measure objectively the severity of a specific hand dysfunction and evaluate subclinical hand impairment in various neurological diseases, including a peripheral neurophaty.[27,28] Several advantages derived from the adoption of this instrument in clinical setting: it does not require calibration or laboratory settings for assessment procedures, it is portable, easy to use and cost effective. This easy-to-apply engineered glove might benefit clinical practice through a good screening routine that firstly, it could save cost and time with respect to traditional or advanced methods requiring more sophisticated technologies and, secondly, it could enable patient assessment and monitoring in home-based setting.

Table 2. Dominant and Non-Dominant Hand Performance of CTS and HC Subjects Evaluated by the Means of the Sensor Engineered Glove System.

	Dominant hand (N = 42)		Non-dominant hand (N = 40)	
Subjects characteristics	HC (F = 14; M = 7)	CTS (F = 14; M = 7)	HC (F = 9; M = 11)	CTS (F = 9; M = 11)
Age range (years)	47 – 74	51 – 72	47 – 76	49 – 74
Spontaneous velocity				
TD (ms)	260.55 ± 14.15	352.33 ± 24.84 (**)	353.59 ± 38.60	454.01 ± 32.12 (*)
ITI (ms)	202.70 ± 12.48	285.11 ± 22.80 (**)	266.99 ± 31.13	247.95 ± 22.79 (ns)
MR (Hz)	2.07 ± 0.14	1.60 ± 0.10 (*)	1.93 ± 0.18	1.56 ± 0.12 (ns)
Maximum velocity				
TD (ms)	200.57 ± 10.55	275.73 ± 20.19 (**)	259.90 ± 28.79	321.57 ± 27.46 (*)
ITI (ms)	152.76 ± 14.08	203.13 ± 11.46 (**)	159.10 ± 18.26	173.87 ± 20.46 (ns)
MR (Hz)	2.79 ± 0.18	2.21 ± 0.11 (*)	2.80 ± 0.24	2.22 ± 0.15 (*)
2 Hz Metronome				
TD (ms)	233.05 ± 9.86	261.23 ± 15.16 (ns)	289.60 ± 26.81	304.42 ± 17.18 (ns)
ITI (ms)	251.18 ± 11.55	238.28 ± 10.84 (ns)	252.99 ± 14.12	210.26 ± 20.32 (ns)
MR (Hz)	2.09 ± 0.03	2.04 ± 0.01 (ns)	1.92 ± 0.08	2.00 ± 0.08 (ns)

Note. In the table are reported the performance of dominant and nondominant hand executed by HC and CTS subjects at spontaneous velocity, maximum velocity, 2 Hz metronome modality. The age range and the number of females (F) and males (M) are reported for each group. The mean ± SE values are reported for considered parameters: TD (touch duration), ITI (inter-tapping interval) and MR (movement rate). Significant differences between HC and CTS groups are reported (**$P < .01$; *$P < .05$). CTS = carpal tunnel syndrome; HC = healthy controls.

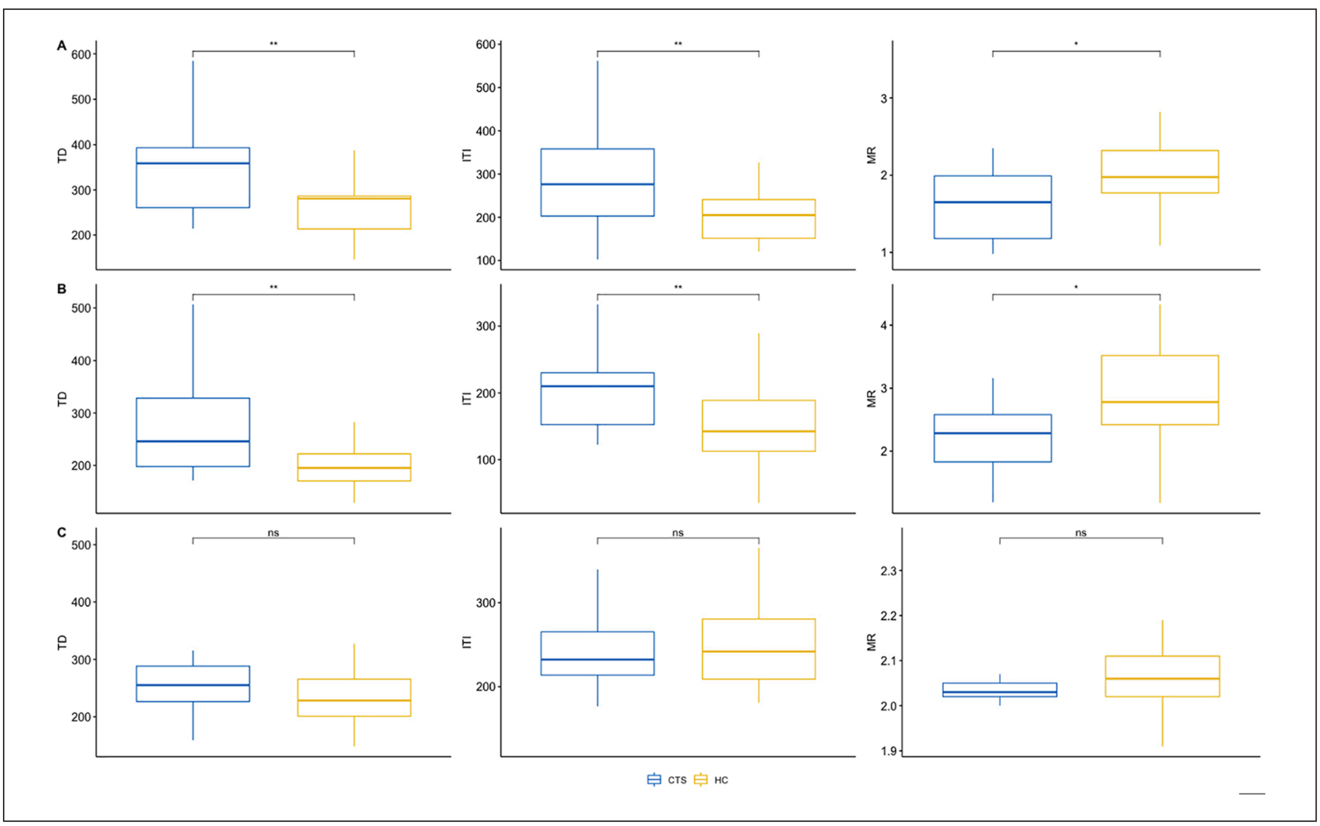

Figure 1. Comparison of dominant hand performance between CTS and HC groups.
Note. The figure shows the performance of the dominant hand at spontaneous velocity (A), maximum velocity (B), 2 Hz metronome (C) mode. For each task, CTS group (N = 21) and HC (N = 21) were compared for TD (touch duration), ITI (inter-tapping interval) and MR (movement rate) parameters of finger opposition movements recorded by the sensor-engineered glove system. Significant differences between HC and CTS groups are reported (**$P < .01$; *$P < .05$). CTS = carpal tunnel syndrome; HC = healthy controls.

Table 3. Hand Function Assessment Provided by the Sensor Engineered Glove System Before and After the Surgery Treatment.

Assessment	Pre	Post
Spontaneous velocity		
TD (ms)	400.13 ± 57.38	281.77 ± 30.21 (**)
ITI (ms)	255.54 ± 25.56	223.48 ± 19.33 (ns)
MR (Hz)	1.73 ± 0.20	2.09 ± 0.15 (ns)
Maximum velocity		
TD (ms)	280.70 ± 33.89	225.13 ± 20.53 (**)
ITI (ms)	169.98 ± 14.96	170.56 ± 9.63 (ns)
MR (Hz)	2.42 ± 0.22	2.63 ± 0.16 (ns)
2 Hz metronome		
TD (ms)	257.66 ± 20.15	222.28 ± 11.88 (**)
ITI (ms)	242.74 ± 18.69	265.18 ± 16.91 (ns)
MR (Hz)	2.00 ± 0.02	2.05 ± 0.01 (ns)

Note. In the table are reported pre- and postsurgery treatment hand performance of CTS subjects (N = 11) evaluated at spontaneous velocity, maximum velocity, 2 Hz metronome modality tasks. The mean ± SE values are reported for considered parameters: TD (touch duration), ITI (inter-tapping interval) and MR (movement rate). Significant differences between pre- and postsurgery treatment are reported (**$P < .01$; *$P < .05$). CTS = carpal tunnel syndrome.

In this study, a quantitative comparison between pre- and postsurgery clinically confirmed CTS and HC was evaluated by analyzing objective performance obtained through HTS, as support for diagnosis, prognosis and effectiveness of therapeutic treatments.

Performance of the HC group resulted similar to that obtained by Signori et al[23] means of a previous version of the sensor-engineered glove: the MR recorded at spontaneous velocity (2.21 ± 0.49 SD *versus* 2.0 ± 0.11 SE) and at maximum velocity (3.03 ± 0.61 SD *versus* 2.80 ± 0.15 SE); the mean TD (209.90 ± 48.90 SD *versus* 260.64 ± 14.54 SE); and the mean ITI (289.1 ± 55.2 SD *versus* 252.06 ± 8.97 SE) recorded with the metronome paced at 2 Hz. Overall results showed that CTS adversely affected the finger opposition movements as demonstrated by the comparison of the 3 kinematic parameters (TD, ITI, MR) with those obtained from HC. The IMRL tasks executed at spontaneous and at maximum velocity were the most effective in highlighting motor skill differences. In particular, TD and ITI parameters were significantly higher, while MR was significantly lower in CTS patients than in HC. Differences in movement features between individuals with CTS and HC resulted clearer when compared at dominant hand. This suggests that CTS affects fine motor skills particularly developed in the dominant hand. Such findings result in line with evidence, suggesting that CTS impairments are particularly associated to the major exposure of the dominant hand in repetitive movements.[29] Therefore, it was highlighted that kinematics deficits of thumb opposition movements affected CTS patients despite normal pinch strength,[17] thus hand motor weakness may be mostly determined by excessive exercises, repetitive work or specific daily activities involving the dominant hand.

Follow-up analysis showed that the overall hand function of CTS-affected individuals resulted generally improved after median nerve decompression. TD parameter observation highlights that CTS affects movement dexterity during precision pinch function.[30] It also let to hypothesize that the inability to consistently coordinate TD when pinching may derive from sensorimotor dysfunction related to reduced motor output and compromised sensory feedback in dynamically regulation of motor function.[31]

All CTS-affected patients were clinically diagnosed. However, symptom duration and impairment level varied. Deficits in thumb kinematics are expected to be greater in patients with advanced or severe CTS,[32,33] including potentially significant deficits in carpometacarpal (CMC) joint due to common concurrent diagnosis (e.g. thumb CMC arthritis). A future study may be carried out to examine the relationship between motion impairment and CTS severity also taking into account other factors such as pain[34] and comorbidities (such as diabetes or thyroid dysfunction)[35,36] that may also impair repetitive motion of finger opposition movements.

Despite the limited sample size, the results of this pilot study support the validity and the sensitivity of the sensor-engineered glove as an innovative instrument for the assessment of hand function in CTS-affected patients. The parameters (ie, TD, ITI, MR) recorded at spontaneous and maximum velocity mode can be considered to distinguish CTS-affected individuals from HC when the dominant hand is affected, and the TD parameter could be a significant outcome measure of sensorimotor function.

Conclusions

The tested device is not a substitute for standard clinical evaluation, but it could be a useful supplementary tool to quantitatively evaluate motor deficits in CTS, providing new insights for evaluative purposes, especially in early-phase or in atypical cases. Thanks to its cost efficiency, easiness to use, and portability, the sensor-engineered glove can certainly play a role in occupational nerve injury related medicine to detect subclinical changes and identify biomarkers of different conditions, thus representing a valid solution for implementing preventative programs.

Although an extended cohort would be needed to more robustly validate the potentially predictive power of this technology, these preliminary results seem to indicate useful performance of the sensor-engineered glove in retrieving quantitative data in CTS context.

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Ethical Approval

This study was approved by our institutional review board.

Statement of Human and Animal Rights

This study respects the ethical standards of the Helsinki Declaration of 1975 as well as the national law.

Statement of Informed Consent

All participants included in the study provided written informed consent.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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