Chapter 2
A Review on Infrared Thermal Imaging as a Tool in Carpal Tunnel Syndrome

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Abstract This research reviews 18 scientific articles concerning the application of infrared thermography (IRT) in the mensuration of diagnostic studies of carpal tunnel syndrome (CTS). In addition, the proposed future challenges in this research area are identified. A review of articles is performed in databases such as PubMed, Scopus, EBSCO, ELSEVIER, Springer, and Oxford Academic using the keywords: carpal tunnel syndrome and (thermography OR infrared image OR thermal image). Its contents, journals publishing the topic, and the year of publication are reviewed, and graphs and cross tables are constructed. Using databases such as PubMed, Scopus, EBSCO, ELSEVIER, Springer, and Oxford Academic, 937 articles are identified, 37 of which were duplicates. The titles and abstracts of the remaining articles were reviewed, and 855 articles were deleted due to exclusion criteria. Eighteen articles were found written in foreign language, five were removed for not covering the topic (three reviews and two on liquid crystal thermography), and four were not available online. Finally, eighteen articles were selected for the full text review, from which 13

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articles meet the CTS diagnostic classification and 5 consider the CTS studies. IRT is a reliable method in the diagnosis of CTS, mainly in the first stage. To improve diagnostic accuracy, it is recommended nerve conduction studies.

Keywords Carpal tunnel syndrome · Cumulative trauma disorders · Infrared thermal imaging · Medical diagnosis

2.1 Introduction

AQ1 Musculoskeletal disorders of the upper extremity, such as tendonitis or nerve entrapments, may be due to the repetitive and forceful use of hands and arms, common among certain occupations. These injuries are the result of small, accumulated tissue damage that is sustained by performing repetitive tasks and are collectively known as cumulative traumatic disorders (CTD). They may also be referred to as AQ2 overuse syndromes, regional musculoskeletal disorders, cervical and brachial disorders, repetitive stress injuries, or repetitive movement disorders. According to data published by the Bureau of Labor Statistics of the United States of America, the incidence of CTD has increased dramatically in recent years, and since 1989, these injuries have accounted for more than 50% of all occupational diseases reported in that country (Rempel et al. 1992).

Carpal tunnel syndrome (CTS) is one of the most conventional compressive and canalicular neuropathies of the upper limbs, which causes hand discomfort and impaired function. CTSs are the result of compression or injury to the median nerve of the wrist (Fig. 2.1) within the limits of the carpal tunnel. CTS patients often experience pain, numbness, tingling, and a feeling of swelling in the median nerve

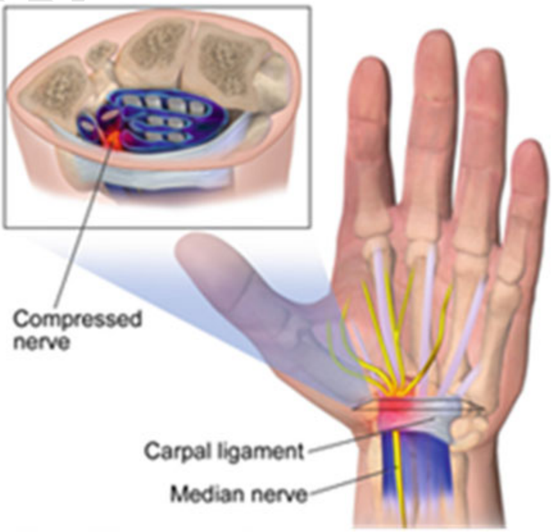

Fig. 2.1 Nerves and ligaments involved in carpal tunnel syndrome

distribution area of the hand. Among other characteristic symptoms of this pathology, it consists of waking up suddenly at night due to numbness and pain in the hand. Both pain and numbness can extend to the upper forearm or even the shoulder (Papež et al. 2008).

According to Ghasemi-Rad et al. (2014), 1 in 5 patients who present the previously mentioned symptoms in the hands is diagnosed with CTS, based on clinical examination and electrophysiological tests. It is estimated that 3.8% of the general population suffers from CTS, with an incidence rate of 276:100,000 per year. This pathology is more frequent in women than in men. The female sex has a prevalence rate of 9.2%, while the male sex has a rate of 6%. The most frequent age ranges for CTS are in a maximum age of 40–60 years; however, there are cases of CTS in young people of twenty years old and on the other hand, in patients older than eighty-six years.

Specifically, in Mexico, the incidence of CTS is 99 per 100,000 people per year and the prevalence is approximately 3.4% in women and 0.6% in men.

Costs caused by this pathology are diverse in nature, as derived from health care, surgery, and rehabilitation. It is estimated that due to this, the United States of America spends approximately 1000 million dollars per year, resulting in the loss of productivity from the affected worker, the economic compensation of the companies, and the days of absence from work (Roel-Valdés et al. 2006).

In Europe, the estimated documented incidence of CTS is 3.5% of the active population between the ages of 16 and 65; however, CTS is not yet recognized as an occupational CTD in all the European Union member countries (Redzwan Habib 2017).

Early detection of CTS increases the probability of treatment success (Alcan et al. 2018). Wright and Atkinson (2019) confirm that the diagnosis begins with clinical history. This is followed by a physical examination and confirmed by an electrodiagnostic evaluation (Kanafi et al. 2018).

According to Schols et al. (2018), there is currently no universal diagnostic method for CTS. There are several tests to detect this pathology, which are palpation tests, such as the Phalen's test and the Tinel's test, and electromyography (EMG), especially nerve conduction studies, which allows the diagnosis of CTS within a certain range, according to Baic et al. (2017).

However, EMG is invasive, so it is uncomfortable for patients, and not totally reliable. Several studies show that routine electrodiagnostic tests have limited sensitivity and specificity for mild CTS cases. Therefore, an expensive and uncomfortable test with uncertain results is usually not convenient, according to Maxel et al. (2014) and Ming et al. (2005)

Electrodiagnostic studies have a sensitivity of 56–85% and a specificity of 94–99% for CTS. These studies should be reserved for atypical cases of CTS, since results may be normal in one-third of patients with mild CTS. It is recommended that electrodiagnostic studies be performed prior to surgery to confirm the diagnosis, since patients with severe CTS are less likely to recover after surgery (Wipperman and Goerl 2016).

There are other techniques such as magnetic resonance imaging (MRI) and ultrasonic detection, which reveal the morphologic changes of carpal tunnel and its contents. However, their results are not reliable (Ming et al. 2005).

Among other tools used in the study and diagnosis of CTS is infrared thermal imaging (IRT), which has been adopted in medicine as a method of monitoring physiology in real time and can be used to document vascular conditions of the autonomic nervous system and musculoskeletal; CTS is one of the conditions in which the use of the IRT image can improve medical diagnosis (Ring and Ammer 2012).

Changes in temperature gradient (decrease and increase) on the surface of the skin or in the center of the body are indicators of disease. Allows to assess changes in metabolism and blood flow, especially in a superficial layer of the skin, according to Boerner et al. (2015) and Cholewka et al. (2010).

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Various studies indicate that the symmetry of the extremities and the trunk will not have a temperature difference on the two sides along a dermatome or thermatoma by more than 0.30 °C and in the forearms no more than 0.90 °C (Uematsu and Long 1976).

The diagnosis of neuromuscular pathology by infrared thermography (IRT) is based on the existence of thermal symmetry and asymmetry between normal and abnormal sites (Fischer 1986).

IRT works by measuring the temperature distribution of a surface, which offers several advantages, as it is non-invasive and non-contact, non-radioactive, painless, with easy reproducibility of results (thermal images) and low cost of operation, according to Živčák et al. (2011).

Due to the advantages of IRT in the provision and treatment of CTS, the purpose of this study is to identify and discuss the application of this technique in studies related to the diagnosis of CTS, as well as its support in conducting medical research studies related to this pathology, and how to identify future challenges that may arise in this research area.

2.2 Methodology

To achieve the above objective, a search strategy is first developed in scientific databases, and then, a review and eligibility of articles are carried out and classified, and their contributions are analyzed.

2.2.1 Stage 1. Search Strategy

Initially, the bibliographic search was performed during the period from August 2018 to July 2019, through the PubMed, Scopus, EBSCO, ELSEVIER, Springer, and Oxford Academic databases, where the following keywords were used: carpal tunnel syndrome AND (thermography OR Infrared imaging OR thermal imaging).

The Boolean operator OR has been used in the present investigation because the word "thermography" presents as synonymous words "Infrared imaging" AND "thermal imaging." It is worth mentioning that the same word structure was used to guarantee consistency in the search through the information sources. Subsequently, duplicate articles were identified in the databases consulted, where a total of 37 articles were identified.

The principles of exclusion and inclusion of articles are as follows:

- Contain in the title or abstract search keywords.
- They must be written in English.
- Liquid crystal thermography or review articles are not included.

2.2.2 Stage 2. Review and Eligibility Results

A review of the results obtained in each database is performed, selecting the research papers whose title and abstract contain the previously determined keywords, that is, the use of infrared thermography (IRT) in relation to the CTS, thus complying with the first selection criterion. Once the initial filter has been approved and the duplicates have been located among the sources of information, the second criterion is evaluated, in which the articles in a language other than English (eighteen of them) are eliminated. The third criterion is to exclude papers on the use of liquid crystal thermography since this article focuses only on the use of IRT. Five articles were excluded because two had liquid crystal as their central topic and three were reviews. Furthermore, six articles were not available, of which five have been requested and only two of these have been provided. Therefore, a total of eighteen articles make up the development of this work.

During the development of this work, the Preferred Reporting Items for Systematic Reviews and Meta-Analysis PRISMA method for reviews was used, whose flow diagram is shown in Fig. 2.2.

2.3 Results

Through the literary search among the databases, a total of 937 articles were found, of which 33 correspond to the PubMed database, 66 to Scopus, 36 to EBSCO, 268 ELSEVIER, 361 to Springer, and 173 to Oxford Academic.

Among the data sources used, 37 duplicate articles were identified, and after reviewing the titles and abstracts of the remaining articles, 855 were eliminated and classified as off-topic according to the first established criterion. Furthermore, 18 articles written in languages other than English were identified (second criterion), and then, 6 articles were not available, so that 5 of these were requested from the

Fig. 2.2 PRISMA flowchart

corresponding authors but only two provided the articles (same researcher). The missing article has not been obtained since emails are not available and neither are the authors' pages.

In addition, 5 articles were rejected due to the third and fourth criterion; that is, 3 reviews and 2 articles on liquid crystal thermography were identified. Therefore, 18 articles form the present analysis, whose methodology search was carried out by two reviewers to guarantee a reliable selection process. Table 2.1 summarizes the results found in the selection process for the development of this bibliographic research, whose results are classified into two sections: *Application of infrared thermography for the diagnosis of CTS (13 articles) and Application of infrared thermography for CTS studies (5 articles)* listed below.

Figure 2.3 illustrates the Journals that publish topics related to the application of IRT in CTS-related studies. In International Symposium of Computer-based Medical

Table 2.1 Articles analyzed and their sources

Database	Found articles	Duplicates	Off-topic articles (1st criterion)	Articles in different language to English (2nd. criterion)	Articles not available	Requested articles	Articles received	Deleted articles (3rd criterion)	Valid articles
PubMed	33		8	9	2	2		3	11
Scopus	66	18	32	7	3	3	2	2	6
EBSCO	36	13	20	2					1
ELSEVIER	268	4	263		1				
Springer	361	2	359						
Oxford Academic	173		173						
Totals	937	37	855	18	6	5	2	5	18

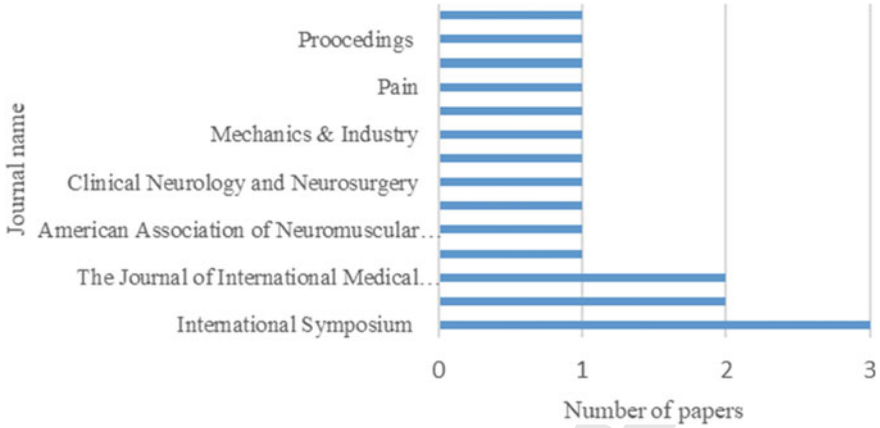

Fig. 2.3 Journals published about the application of IRT in CTS-related studies

Systems, Computational Intelligence, and Computer Science, 3 papers have been published in total, and in the Journal of International Medical Research and The Journal of Hand Surgery, two papers have been published in each one. The rest of the journals only have one publication on the subject.

Figure 2.4 illustrates the number of articles analyzed per year. It can be seen that from 1987 to 2017, there is only one publication per year, except for the years 1995, 2005, 2007, and 2008, which had 2 articles.

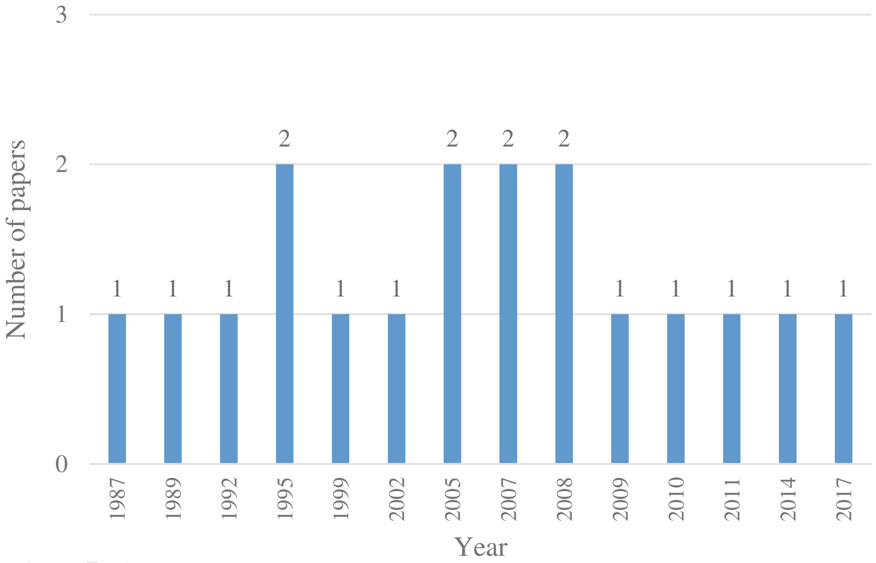

Fig. 2.4 IRT as a tool in CTS publications by year

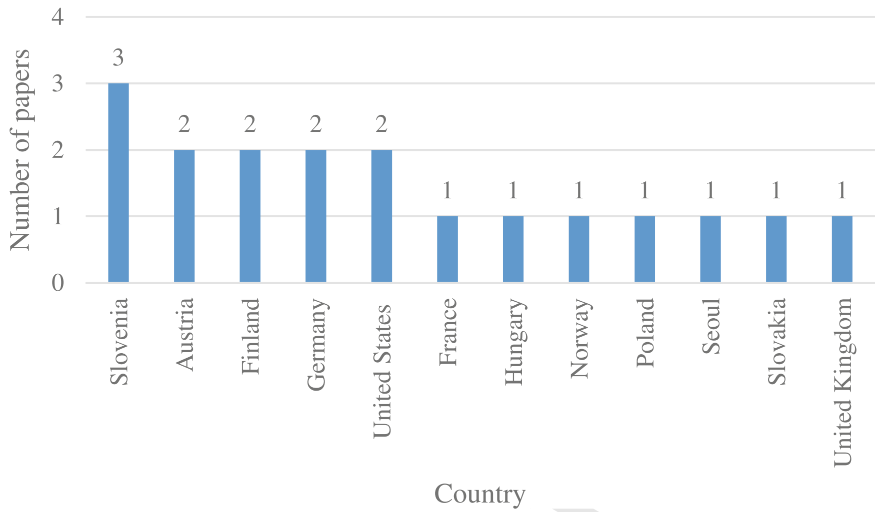

Fig. 2.5 List of publications by country

Figure 2.5 illustrates the countries that have developed research related to the use of IRT as a tool for CTS. It can be seen that Slovenia presents the highest number of articles, that is, 3 publications, followed by Austria, Finland, Germany, and the United States with 2 publications, while France, Hungary, Norway, Poland, Seoul, Slovakia, and the United Kingdom present only one publication each, regarding IRT application issues in CTS.

The departments with greater commitment regarding the use of IRT in CTS studies are associated with neurology, neurosurgery, pathophysiology, rheumatology, among others.

2.3.1 Application of Infrared Thermography for CTS Diagnosis

Below is a series of results from various research works focused on determining if IRT is actually a useful tool for diagnosing CTS.

Five out of eighteen studies focus on determining the effectiveness of IRT as a diagnostic method of CTS, by analyzing thermal images of hands on their dorsal and palmar parts, between healthy people and patients with CTS. These authors agree that the dorsal side of the hand provides more successful results when diagnosing CTS and therefore is more important than the palmar area of the hand. Indeed, thermography is a potential method in the diagnosis of CTS (Papež et al. 2008, 2009; Tchou et al. 1992; Tkáčová et al. 2010; Živčák et al. 2011).

Papež et al. (2009) establish that IRT allows correct classification of 72.2% of the hands, between healthy and pathological, based on the dorsal part of the hand, while >80% when evaluating severely affected hands with healthy hands. On the other hand, they obtained success rates for the classification of healthy hands with CTS pathologies close to or greater than 80% (Palfy and Papež 2007; Papež et al. 2008; Tchou et al. 1992; Tkáčová et al. 2010).

AQ4

While Živčák et al. (2011) were analyzed a database of 268 thermograms, classified into 120 healthy hands and 14 hands with clinically diagnosed CTS. The temperature distribution was observed, and the partial temperatures were calculated in five regions: center point of the carpophores (D1), center point of the metacarpals (D2) and the tips of the third finger from the proximal phalanges (D3) and the intermediate phalanges (D4) to the distal phalanges (D5), and the median nerve index (MI = D1–D5).

In addition, artificial intelligence systems have been used to improve the diagnosis of CTS (Palfy and Papež 2007; Papež et al. 2008, 2009; Tkáčová et al. 2010).

In one of these studies, the reliability of the method was tested through artificial neural networks for data analysis, using 112 thermogram shots (26 healthy hands and 30 pathological ones), and specifically divided the hand into 12 areas of interest: the fingers (five segments), metacarpus (five segments), and carpus with wrist (two segments). In addition, they determined that the dorsal side of the hand provides greater success results when diagnosing CTS, and therefore, it is more important than the palmar (Papež et al. 2008).

Baic et al. (2017) verified the usefulness of IRT as a diagnostic method of CTS and analyzed its possible use for monitoring the healing process in CTS surgery. Images were obtained on both hands of palms and back to obtain temperature gradients. CTS surgery patients were examined before and after surgery to verify treatment effects. Their study involved 15 patients with CTS, 15 patients gone through surgery for CTS, and 15 healthy volunteers. The thermal images analyzed showed that healthy controls and patients, as well as the manual thermal image performed before and after surgery, differ completely. Thermal analysis shows that the thumb recovers faster than the rest of the fingers, which could be due to thenar eminence, a very strong muscle that can protect nerves and blood vessels. In fact, fingers, heart, and index are exposed to the effects of the CTS more than the thumb.

Herrick and Herrick (1987) used thermography to obtain images of the cervical spine, shoulders, forearms, and hands of a total of 90 patients, of whom 55 had CTS. Their studies to diagnose CTS by thermography establish that the results were effective and sensitive in differentiating the diagnosis of CTS from other peripheral compressive neuropathies, including cervical radiculitis, thoracic outlet syndrome, ulnar tunnel syndrome, and Guyon canal. The results reached an overall specificity of the thermographic studies of 80% with sensitivity of 96%, while when considering only the CTS patients, the diagnostic success rose to 97% with 100% of sensitivity.

Palfy and Papež (2007) used 44 thermograms of healthy and pathological hands (23 pathological and 21 healthy) to which he measured their temperatures and divided the hand into the following areas of interest: fingers (5 segments), metacarpus (middle part of the hand: 5 segments), and the carpus with the wrist (2 segments) to determine the effectiveness of IRT as a method of diagnosing CTS. They reached success rates for the classification of healthy hands with CTS pathologies close to or greater than 80%.

Papež et al. (2009) segmented the hand region as previously described and used a database of 502 thermal images including 132 healthy and 119 pathological hands to test the effectiveness of IRT in diagnosing CTS. They obtained success rates from the classification of healthy hands and CTS pathology of 72.2% based on images of the back and 80% of the hands when they were only seriously affected and considering healthy hands. Additionally, they found that the dorsal side of the hand provides more successful results when diagnosing CTS, and therefore, is more important than the palmar area of the hand.

Tkáčová et al. (2010) recorded 14 thermal images (7 healthy and 7 affected) and measured the temperature of each hand divided into 5 segments to determine the level of effectiveness of IRT to diagnose CTS. The success rates found for classifying healthy and pathology CTS hands approached 80%. In addition, they identified that the dorsal side of the hand provides greater success results when diagnosing CTS, and therefore, is more important than the palmar area of the hand.

Unlike the works previously analyzed, they studied the thermal responses in 6 patients with CTS and 5 healthy people, so that the patients' hands were excited. The procedure consisted of asking the participant to wash and dry his hands and then immediately place his hands on a plate to obtain his thermal images. The patient was then asked to place the palms of both hands in ice cubes for 60 s. This was done to induce a sympathetic nerve stimulation. At the end of the stimulation phase, the participant placed his hands on the analysis table, to continue with thermograms takes. Using infrared views, they demonstrated that the hands with CTS give a thermal response. Thus, the difference increases if the patient has CTS, because the thermal pattern of the hand is different. The temperature variation is weak for healthy people; instead, it rises for patients. It also shows that the temperature variation must be above or below 0 °C, which corresponds to a vasoconstriction or the vasodilation of the veins. Also, this study proved that CTS can cause vasomotion problems in the thumb and index finger, where paresthesia is felt. From this, it follows that the IRT method is sensitive to median nerve variation (Maxel et al. 2014).

AQ5

Ming et al. (2005) implemented a research concerning sympathetic pathology in CTS and the benefits of IRT in the diagnosis of this pathology. Temperatures were measured at the tips of the fingers, central thenar point, and eminences in 38 pathological hands and 41 healthy hands. They calculated the thermal differences between the fingertips. The results showed highly significant differences in the temperatures of the median nerve distribution area in the hands among the CTS and the control group. The differences between the distribution area of the median and ulnar nerve were also highly significant in the hands with CTS. The susceptibility and specificity of infrared thermography were 84% and 91% accordingly.

Orlin et al. (2005) included 22 patients with CTS symptoms and 16 healthy subjects, who underwent two-hand exercises as follows: (a) passive dorsiflexion in the radiocarpal joint (range 0–75°) and (b) hand exercise with hand booster (one compression per second) with wrist in neutral position for a maximum period of 90 s (if no fatigue occurs before). Before and after the manual exercise, the temperature was measured at the fingertips. The findings in thermography showed interrelationship with the deterioration of symptoms after manual exercise. A remarkable reduction in fingertip temperature was determined after the exercises performed by the patients. However, no changes were identified in healthy subjects. Low-grade CTS patients had a reduction in skin temperature caused by increased sweating.

In the same context, Tchou et al. (1992) recorded 122 thermograms, where 61 patients presented CTS and 40 volunteers healthy patients. They measured the temperatures of the thumb, index, and middle fingers of each hand from the phalangeal metacarpus of the junction to the tip of the fingers and toward the width of the fingers in order to test the effectiveness of IRT in the diagnosis of CTS. They obtained success rates for the classification of healthy hands with CTS pathologies close to or greater than 80%. Furthermore, they determined that the dorsal side of the hand provides more successful results when diagnosing CTS, and therefore, it is more important than the palmar area of the hand.

Park et al. (2008) determined that IRT does not contribute to the detection of CTS. In their research work, the feasibility of said method to diagnose unilateral CTS was evaluated. They evaluated a population of 28 patients with this pathology, where 19 of 28 patients with unilateral CTS manifested relevant differences in the temperature of the thumb tip, index, and middle finger. Meanwhile, 13 of these 19 patients had significant differences in at least one of the regions not inverted by the median nerve passing through the carpal tunnel. Of the 28 patients with unilateral CTS, only 4 had significant thumb, index, or middle finger tip temperature and only 2 had significant temperature in at least one of the regions that are not innervated by the median nerve passing through the carpal tunnel.

Lang et al. (1995) conducted a more in-depth study to assess the functions of the thick and thin nerve fibers in CTS, in order to deduce whether the data of the thin nerve fibers can contribute to the diagnosis of CTS. Twenty-two patients and 16 participants were studied, examining motor and sensory nerve conduction, vibration tests, thresholds of hot and cold sensations, upper pain threshold magnitude and burst response, as well as sympathetic reflexes before and after median nerve decompression. Thermography and photoplethysmography of the injured hand were recorded before and 1, 3, 6, and 12 months after median nerve decompression. Time comparisons were made using univariate analysis of variance in a repeated measures design and post hoc comparisons with the Newman-Keuls test or the Wilcoxon-Wilcox test. The T test was used to compare patients and control subjects and finally the Pearson correlation or the Spearman rank correlation.

The preoperative heat sensation (5.59 ± 0.62 °C) and cold (7.11 ± 0.9 °C) sensation thresholds were found to increase significantly in the index finger compared to control subject's data. After median nerve decompression, the cold and hot sensation thresholds enhanced significantly only in the index finger ($p < 0.05$). The highest rating of pain intensity by harmful mechanical stimulation was (30 ± 15%) in patients. The reflective decrease in skin temperature on the palm side of the third and fifth fingers tended to be deeper ($p < 0.01$) in patients than in healthy subjects. However, no significant differences were reported between the third and fifth fingers.

Regarding the response of the dilator vessel locally around the stimulation zone, no significance was detected among patients (0.71 ± 0.13 °C) and control subjects (0.88 ± 0.18 °C), even after median nerve decompression.

The data on the functions of the thick and thin nerve fibers were not significantly correlated at any time during surgical treatment, i.e., before or after. As far as thermography and plethysmography studies are concerned, they showed no significant relationship. Therefore, it can be inferred that these methods do not contribute to the diagnosis of CTS.

Reilly et al. (1989) found the characteristic thermal patterns in the CTS in 23 patients with a clinical history that suggested suffering from this pathology. Thermography and median nerve conduction tests (NCTs) were compared. Six patients presented normal NCTs, where two were thermographically normal. On the other hand, 17 patients presented non-normal NCTs, 12 unilaterally and 5 bilaterally. Sixteen participants showed non-normal thermal results. Six of eleven patients with right CTS presented hot right wrist and only one with hot left wrist. Regarding the Tinel´s test, all obtained negative results (present in 8 of 17 with CTS). Similarly, the Phalen´s test did not show a positive result in 11 of 17 patients. Therefore, it correlated significantly with thermal abnormalities. However, despite having found thermal irregularity in wrists and fingers, no clear diagnostic pattern was found. Similarly, no implication found among clinical tests and thermography or conduction tests. Thus, nerve conduction studies offer the most accurate diagnosis of CTS.

2.3.2 Infrared Thermography Application for CTS Studies

Lang et al. (1994) assessed the functional profile of pain-related middle nerve fibers due to CTS. The objective was to predict pain in CTS by analyzing the functional deficits of certain nerve fibers. The frequency and intensity of pain were followed for 14 days in 23 patients with CTS and 16 volunteers. Measurements were made of distal motor latency (DML) of the median nerve. Through thermotest, cold, heat, and heat pain perception tests were performed. Thermograms and photoplethysmograms were also obtained on the hand stipulated for surgical treatment. Once all the tests were performed, data were analyzed with the Kolmogorov-Smirnov test. It was determined that CTS-induced pain was situated in fingers 1–4 and palm. Intensity and frequency of pain attacks were significantly correlated ($p < 0.01$). The same was true for pain intensity and area of pain ($p < 0.05$). Greater significance was observed in the median nerve DML in patients (6.0 ± 1.4 ms.), compared to volunteers (3.6 ± 0.5 ms.).

Patients showed significant increase in heat and cold perception thresholds when compared to control subjects. After clinical intervention of the median nerve, pain levels were significantly reduced in the index and small fingers. There was no significant correlation between pain intensity and other neurophysiological parameters. However, significance was obtained between the area of pain and DML ($p < 0.05$).

Pain intensity due to CTS was predicted with $R = 0.72$ ($p < 0.001$, $n = 23$). The inclusion of more parameters as independent variables did not contribute to the prediction of pain due to CTS.

Ming et al. (2007) studied the recovery of patients after CTS surgery. Thermograms were obtained from the hands before and after CTS release between 22 patients and 41 volunteers. Subsequently, they obtained the temperatures of the fingertips from digit 1 to digit 5, the central point of the thenar and hypothenar eminences, the mean nervous index, and the temperature difference among the median and the area of distribution of the ulnar nerve. Based on the outcomes of IRT, it is determined that regulation of blood flow in CTS is abnormal, which is probably due to the altered regulation of the sympathetic motor vessels, and that circulation is normalized along with the relief of other CTS symptoms documented 6 months post-surgery.

Ammer et al. (2002) focused on his research in establishing a normal temperature range in the finger joints. For this purpose, the hands of 140 participants were thermographically evaluated, of which 37 patients had symptoms of painful osteoarthritis, 21 were diagnosed with arthritis, and 22 with CTS. Cold water tests were then performed to observe the pattern of temperature recovery. To establish the normal temperature ranges, a standard deviation value was defined, as well as the median and interquartile range. The results showed that, in the case of non-symptomatic joints, the highest temperatures were found in the thumb joints and the lowest in the little finger. However, the temperature of the interphalangeal joints of the ring finger and the little finger was lower than the non-symptomatic joints. The temperature of the colored joints in the walls and certain woofer joints recovered more quickly than other joints after a slight cold spell.

Ammer (1999) studied 154 hand thermographs to identify patients with thoracic outlet syndrome or CTS from healthy subjects. This is through the presence of thermal asymmetry between the index and little fingers, defined by the temperature difference of 0.5 °C between those fingers. According to neurography and thermographic criteria, the hands were classified into four groups: healthy controls, CTS, thoracic outlet syndrome, and the combination of the syndromes. Subsequently, a discriminant analysis of the asymmetries in the groups was carried out. As a result, a correct classification of 44.8% of the cases was obtained.

Once the syndrome combination has been passed to the thoracic outlet, the number of correct classifications increased to 63.3%. Values of 71.6 and 42.9% were obtained, for sensitivity and specificity of pathological temperature differences for the diagnosis of thoracic outlet syndrome. The sensitivity was 11.9% and the specificity 42.9% for the comparison controls and CTS.

Therefore, it is possible to identify patients with thoracic outlet syndrome by means of temperature distribution in the hand, but not for CTS cases. Table 2.2 is shown below, summarizing the results previously presented.

Table 2.2 Summary of results found

Reference / Ref.	Country	Journal	Type	Participants	Method	Temperature measurement regions	Results
Baic et al. (2017)	Poland	Medicine	CTS	15 patients with CTS	Obtaining temperature gradients by palm and back thermograms of each hand	Palm and back of each hand	IRT may be useful in diagnosing CTS
			Diagnostic	15 patients gone through surgery for CTS			
				15 healthy volunteers			
Maxel et al. (2014)	France	Mechanics & Industry	CTS	6 STC patients	Energize hands of patients (hot-cold changes) and analyze their thermal response	Palm and back of each hand	Thermograms show CTS hands give thermal response
			Diagnostic	5 healthy people			
Živčák et al. (2011)	Hungary	International Symposium on Computational Intelligence and Informatics	CTS	14 pathological hands	Analysis of the temperature distribution of the whole hand and calculate partial temperatures	Central point of the carpophores & metacarpus, tips of the third finger from the proximal phalanges, intermediate phalanges to the distal phalanges and the median nerve index	Thermography is a potentially method in the diagnosis of CTS
			Diagnostic	120 healthy people			
Tkáčová et al. (2010)	Slovakia	International Symposium on Applied Machine Intelligence and Informatics	CTS	7 pathological hands	Skin temperature of both hands by computer-assisted IRT	The hand was divided into 5 segments	Classification of healthy hands and with CTS pathologies close to or greater than 80%
			Diagnostic	7 healthy hands			

(continued)

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Table 2.2 (continued)

Reference Ref.	Country	Journal	Type	Participants	Method	Temperature measurement regions	Results
Papež et al. (2009)	Slovenia	The Journal of International Medical Research	CTS	502 thermal data	Use of thermal images of palm and back on hands and artificial neural networks for the diagnosis of CTS	Fingers (five segments), metacarpus (five segments), and wrist carpus (two segments)	Classification of 72.2% of the hands, between healthy and pathological, based on the dorsal part of the hand, while > 80% when evaluating severely affected hands with healthy hands
			Diagnostic	132 healthy hands			
				119 pathological hands			
Papež et al. (2008)	Slovenia	The Journal of International Medical Research	CTS Diagnostic	26 healthy hands 30 pathological hands	Compare thermal images (back and palm) with respect to a reference, using an artificial intelligence system	The fingers (five segments), metacarpus (five segments), and carpus with wrist (two segments)	Classification of healthy hands and with CTS pathologies close to or greater than 80%
Park et al. (2008)	Seoul, Republic of Korea	American Association of Neuromuscular & Electrodiagnostic Medicine	Diagnostic STC	350 patients	Measure finger temperature by IRT in patients with unilateral CTS	Tip of thumb, index and middle, thenar area, hypothenar area, back of hand, and forearm	IRT is not useful in diagnosing unilateral CTS

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Table 2.2 (continued)

Reference Ref.	Country	Journal	Type	Participants	Method	Temperature measurement regions	Results
Ming et al. (2007)	Finland	Clinical Neurology and Neurosurgery	Medical study	22 CTS patients 41 healthy volunteers	Obtain thermograms before and 6 months after CTS release and measure the temperatures of the fingertips	Fingertips from digit 1 to digit 5, central point of thenar and hypothenar eminences, median nerve index, and the temperature difference between the median and the ulnar nerve distribution area	Found abnormal regulation of blood flow in CTS, possibly due to impaired sympathetic motor vessel regulation and that circulation normalizes along with relief of other CTS symptoms recorded 6 months after surgery
Palfy and Papež (2007)	Slovenia	International Symposium on Computer-Based Medical Systems	CTS Diagnostic	23 pathological hands 21healthy hands	Segmentation of hand thermograms and temperature extraction and image analysis to diagnose CTS	Fingers (5 segments), metacarpus (middle part of the hand—5 segments), and the carpus with the wrist (2 segments)	Classification of healthy hands and with CTS pathologies close to or greater than 80%
Ming et al. (2005)	Finland	Pathophysiology	CTS Diagnostic	38 pathological hands 41 healthy hands	Measure temperatures in regions of hands to clarify sympathetic pathology in CTS	Fingertips, central thenar point, and eminences	IRT with 84% sensitivity and 91% specificity
Orlin et al. (2005)	Norway	European Journal of Neurology	CTS Diagnostic	22 patients with symptoms of CTS 16 control subjects	Study microvascular perfusion in fingertip skin and skin temperature during dorsiflexion of the hand before and after manual exercise	Fingertips	Thermography findings correlate well with deterioration of symptoms after the manual exercise test

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Table 2.2 (continued)

Reference Ref.	Country	Journal	Type	Participants	Method	Temperature measurement regions	Results
Ammer et al. (2002)	Austria	International Thermology	Medical study	98 patients 42 participants	Cold water test in patients to observe the temperature recovery pattern	Index finger and little finger	It is inferred that normal temperature range of the finger joints by thermography did not prove to be clinically useful
Ammer (1999)	Austria	Proceedings of The First Joint BMES/EMBS Conference	Medical study	77 patients	Thermograms taken during the hyper abduction test and the modified Adson maneuver to measure temperatures and discriminant analysis of the data grouping	Ring fingers, thumb, and little finger	CTS patients and healthy people were classified correctly in 44.8% of cases. By transferring combined CTS to the thoracic outlet the number of correct classifications increased to 63.3%
Lang et al. (1995)	Germany	MUSCLE & NERVE	CTS Diagnostic	22 patients 16 control subjects	Examine sensory and motor nerve conduction, vibration tests, and thresholds for hot and cold sensations, magnitude of upper pain threshold and flare response, as well as sympathetic reflexes before and after median nerve decompression	Second, third, and fifth fingers; thenar and hypothenar and the area around the site of the mechanical stimuli and skin and skin stimulation between the second and third finger	Assessment of the flare and sympathetic response by IRT and photoplethysmography did not contribute to the diagnosis of CTS

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Table 2.2 (continued)

Reference Ref.	Country	Journal	Type	Participants	Method	Temperature measurement regions	Results
Lang et al. (1994)	Germany	Pain	Medical study	23 patients with CTS 16 volunteers	Obtaining thermograms on painfully stimulated hands and fingers	Fingers 2, 3, and 5, the thenar and hypothenar, the area around the site of the mechanical noxious stimulation of the skin between the index and middle fingers and in a reference area around the skin between the ring finger and the little finger	The sweat motor nerve fibers are not considerably damaged by CTS. The intensity of pain due to CTS depends on disturbances of peripheral and central nerve functions
Tchou et al. (1992)	United States	The Journal of Hand Surgery	CTS Diagnostic	61 patients with unilateral CTS 40 volunteers	Thermographic examinations for classification of healthy and pathological hands	Thumb, index, and middle fingers	Classification of healthy hands and with CTS pathologies close to or greater than 80%
Reilly et al. (1989)	United Kingdom	British Journal of Rheumatology	CTS Diagnostic	23 patients with CTS	Evaluation of CTS thermal patterns, comparing tests of mean nerve conduction and thermography	Hands and wrists	No clear diagnostic pattern of CTS was found by IRT
Herrick and Herrick (1987)	United States	The Journal of hand surgery	CTS	90 patients	Obtaining thermograms to get diagnoses and stress series Studies were conducted to differentiate CTS from peripheral neurovascular injuries	Cervical spine, shoulders, forearms, and hands	General specificity of 80% and sensitivity of 96%. When considering only CTS patients, the diagnostic success was 97% with 100% sensitivity

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2.4 Discussion

It has been determined that IRT is useful in the diagnosis of CTS (Baic et al. 2017; Herrick and Herrick 1987). In addition, Baic et al. (2017) support its application to monitor the recovery process, and Herrick and Herrick (1987) consider its application in treatments and preventive measures of the CTS, which could eliminate the high cost of the loss of labor and medical care.

Employing IRT in conjunction with intelligent computing systems improves the diagnosis of CTS (Palfy and Papež 2007; Papež et al. 2009; Tkáčová et al. 2010). On the other hand, several investigations agreed on their findings about IRT, as effective in the diagnosis of CTS, particularly in the first stage (Lang et al. 1995; Maxel et al. 2014; Ming et al. 2005; Orlin et al. 2005).

However, IRT is not recommended when CTS is severe (Papež et al. 2009). On the other hand, they supported that IRT is used in the diagnosis of unilateral CTS, but limited in bilateral CTS (Tchou et al. 1992). Conversely, the use of IRT in the diagnosis of unilateral CTS is not recommended (Park et al. 2008).

The measurements made by IRT demonstrate blood flow regulation abnormality in CTS. This is probably due to the sympathetic vasomotor disturbance and the simultaneous normalization of the relief of CTS symptoms and the circulation (Ming et al. 2007). Ammer et al. (2002) determined that the definition of the normal range for temperature readings from thermal images of the finger joints has not been shown to be clinically useful. Whereas Ammer (1999) determined that patients suffering from CTS, it is indistinguishable from normal patients in thermal imaging by applying tests for thoracic outlet syndrome.

Lang et al. (1994) established that the intensity of pain caused by CTS relies on the disturbances of the peripheral and central nervous functions. Finally, the absence of a clear CTS diagnostic pattern is pointed out, since no association has been found between clinical tests and thermography or conduction tests (Reilly et al. 1989).

2.5 Conclusion

IRT imaging is a useful technique for diagnosing CTS, especially at an early stage. However, its precision is limited in bilateral disorders, while it is very useful in unilateral CTS. An attempt has been made to find a diagnostic guideline for CTS, but has not yet been achieved. It is considered that to achieve a completely reliable diagnosis of CTS, it is necessary to carry out nerve conduction studies.

Overall, IRT imaging provides useful information for prompt detection, treatment, and even preventive measures that can remove the high costs of lost human resources and medical care related to CTS.

2.6 Future Works

~~Based on the results obtained, it is proposed that in future studies, in case of CTS diagnosis be feasible, the identification of new unknown interrelation, among skin surface temperatures and entrapment syndromes of nerves or even the results of electromyography should be studied in depth~~ (Palfy and Papež 2007; Papež et al. 2008, 2009).

Furthermore, it is proposed that to determine how the recovery process will unfold and how longer it will take, more research that includes measurements after completion and beyond just 4 weeks after surgery is needed, allowing an objective evaluation of the procedures used (Baic et al. 2017). On the other hand, it is recommended that the analyses carried out always be based on statistical analyses (Tkáčová et al. 2010). In addition, a quantitative assessment of neuropathy and the importance of the diagnostic method are suggested (Tkáčová et al. 2010).

Moreover, given the current working conditions, it is considered that the studies have been focused on the population with restricted patients, so it is now required to be generalized. Also, the robustness of the tests should be studied in depth, to understand why the thermal signature of the CTS was generally positive but also negative in particular cases.

It is also suggested to analyze the cause of kinetics in thermal reactions among one patient and another, which allows optimizing the experimental protocol (duration on excitation, type of excitation, duration analysis, type of post-processing, etc.). Additionally, it is important to take into account the exclusion criteria selected (Maxel et al. 2014).

Additional follow-up studies should be considered to explain the advancement of neuropathophysiology to distinguish diverse stages of neural lesions and to investigate the reversibility of functional abnormalities (Ming et al. 2005). Likewise, studies focused on increasing diagnostic susceptibility and specificity are required in cases of chronic unilateral CTS and recurrent postsurgical CTS, since almost 30 years ago (Tchou et al. 1992).

Studies are also needed on the reproducibility of IRT digital recordings. In addition, further studies are suggested on the functional impairment of different types of nerve fibers in relation to nerve compression. Employing digital IRT, nerve conduction studies, and, for example, the tactile sensitivity test could provide information on the responses of the various groups of fibers under such conditions (Ming et al. 2007).

Additional information must be obtained from observing the recovery of temperature after a mild attack of cold. It is possible that the assessment of finger temperatures from the reference database of normal human body thermographs will solve the problem of establishing a normal range of finger joint temperatures in the nearby future (Ammer et al. 2002).

In general, it is recommended to continue with the review of related research between CTS and IRT which will allow to enrich this work, so that the reliability of IRT as a diagnostic method for CTS is firmly demonstrated, as well as a support technique for studies related to this pathology involving prevention, pre-operative and post-operative studies, assessment of short-, medium-, and long-term treatment, among other research that will foster the continuity in this topic given its importance and support for the prevention and treatment of CTS, which contributes to improving the quality of life of patients suffering from it.

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