Using Clinical Thermography as Diagnostic Complementary Procedure for Hand Arm Vibration Syndrome

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SUMMARY

Introduction: Hand-Arm Vibration Syndrome is an occupational condition that affects people exposed to vibrating tools in the workplace and needs an accurate quantitative and objective diagnostic test to aid clinicians in the judgment of the degree of injury and correspondent treatment. An objective assessing method is needed to provide a permanent evidence record of the degree of injury.
Methods: Medical thermography was used with a developed objective mechanic provocation test involving vertical vibration exposure of hands, for 2 minutes at 31.5Hz of vibration frequency and 36 mm/s2 of vibration magnitude, which was followed by a vascular provocation challenge of the hand for a period of 1 minute at 20°C. Images were taken during the whole procedure. In order to assess the peripheral temperature changes of the hand a computational model was developed and the images standardised and analised.
Results: It was possible to discriminate between degrees of injury groups ($p<0.05$) but not individuals. It was possible to identify through medical thermography the affected fingers and its temperature changes quantified assessing objectively the stage of the injury.
Conclusion: The proposed method is objective and repeatable, can provide information of the evolutionary stage of the condition. Medical thermal imaging can be used as diagnostic tool to provide evidence of occupational condition affecting upper limbs in support to medical history in medico-legal liabilities.

1. INTRODUCTION

1.1 Vibration

The term vibration within this experiment is recognised as mechanical movement that oscillates in the form of a wave about a fixed point. Each wave produced by vibration is characterised by four components: frequency [Hz], acceleration [m/s^2], velocity [m/s] and displacement [m] (12).

1.2 Hand transmitted vibration

Vibration is transmitted and absorbed by the hand when an individual holds a vibrating tool. Someone using a vibrating tool perceives the vibration though tactile receptors in the skin creating a risk based in the type of vibration and time of exposure to the vascular, neural and musculoskeletal systems. Actions are needed to minimize it and when the problem becomes apparent, medical professional might be required to classify the nature and severity degree of the problem (12).

1.3 Hand-Arm Vibration Syndrome

Workers exposed to hand transmitted vibrations may experience various vascular, neurological musculoskeletal related disorders of the hand, although not all frequencies, magnitudes or durations of vibration cause the same effects. In order to enable reporting and comparison of exposures, there is a need for the exposure to be measured and evaluated using defined standardised protocols. Furthermore it is necessary to identify what should be measured and how measurements should be expressed, taking in account the components of vibration and assessing their impact according to criteria such as the probability of a specific severity for a specific form of the disease. With current assessment protocols it is also difficult to gauge the importance or weight of different frequencies, the axes of vibration, vibration

magnitude and daily exposure durations for HAVS (9).
It is understood that Hand-Arm Vibration Syndrome is provoked by a progressive and excessive exposure to vibration over a prolonged period of time. The term HAVS is used to describe a range of injuries that can be incurred after excessive exposure to vibration when using vibrating tools with Vibration White Finger (VWF) syndrome having the highest prevalence, clustered around certain industries (7).
This disorder is characterised by a complete episodic closure of digital blood vessels. Although either central and/or local pathogenic mechanisms may be involved, this pathogenesis is not fully understood yet because the pathophysiological mechanisms underlying muscular disorders in workers operating vibration tool are often unclear. Disorders of organs, nerve fibre dysfunction resembling entrapment neuropathy and diffuse or multi-focal neuropathy are thought to be related to working with vibrating machines causing neuropathy to peripheral nerves, mainly sensory ones but also those of the motor and nervous system. Any of the nerves of the upper limbs may also be affected as this disorder is not confined to the digits. It can also extend to the palm and the arms (10).
The consumption of alcohol, tobacco or drugs as well as the individual lifestyle also influences the risk of contracting HAVS. Age is another important factor that is thought to be linearly correlated with vibration exposure history. People that work a long time exposed to hand transmitted vibration tend to be more susceptible to acquiring the syndrome. According to a 2004 study from Sweden that examined working women exposed to hand-transmitted vibration, there is no difference between genders with respect to power absorption during vibration exposure (5).
The main symptoms of HAVS are apparent in the fingers. Patients report that these can become numb and turn white, and spasm may occur due a lack of blood supply. The main symptoms of HAVS are: vascular effects, which are expressed as coldness and blanching of one or more fingers and neurological effects manifest themselves as tingling sensations, “pins needles” and numbness. The neurological symptoms can arise independently and pre-date vascular symptoms (9).
In most individuals the condition is not severe and attacks only cause minor discomfort. In more extreme cases, however, repeated or constant ischemic episodes can result in skin ulcers and even gangrene requiring surgery or amputation. Picking up small objects such as pins or nails will become more difficult as the sensory capacity of the fingers decreases, along with a loss of strength and grip of the hands. Pain, tingling and numbness in the arms, wrists and hands can make sleeping difficult (10).
HAVS is very difficult to prove in court, the process is slow, the evidences should be strong, and courts are facing the task of striking a balance between suspicious false claims and awarding legitimate compensation. A claimant’s detailed, clear and accurate but subjective description of symptoms is not enough. Support, for example by objective photographic evidence of vascular symptoms corroborated by expert medical opinion has shown to be helpful (16).
HAVS can present secondary Raynaud’s phenomenon, where exposure to a mild cold stress (water at 20ºC for 1 minute) provokes intense and often painful narrowing of peripheral blood vessels and thus a reduction of the blood supply (hence the white finger) followed by unusually long recovery times where dilatation of blood vessels and re-perfusion only eventually cause the affected limb to warm up again (7). These changes can be monitored and quantified with digital thermography given the right methodology is followed.
An Italian physician has performed the first study on occupational lesions from vibrating tools with medical thermography, he found that the most dangerous vibrations to the human extremities were in the range from 30Hz to 80Hz. The methodology followed by this study was to take a thermal image of the hands before a cold vascular provocation, then using an exposure to water at 5ºC for 5 minutes, followed by thermographic recordings in 5 minute intervals. This test was not considered 'fair' in law due to the difficulty in turning the fingers white without previous exposure to vibration. The infrared thermal imaging technique was compared with the photoplethysmyography modality. He concluded that thermography is a suitable choice for a diagnostic method in liability and insurance cases, and also in occupational and forensic medicine (1).
A year later the same researcher demonstrated that the dorsal hand after vibration exposure presented to be warmer at the radial region and cooler at the ulnar region. He suggested the usage of thermography for the assessment of vascular, nervous and osteoarthritis diseases, strongly proposing the use of medical thermography as a diagnostic tool for pathologies involving vibration and prognostic data for vascular or neuronal traumatic lesions or in sudden atrophy (2).
The current exposure limit value to vibration is defined in the 2002 version of ISO 5349 and is addressed by a European Directive recommended for all member states to incorporate into their national legislation. The directive established as exposure limit a value of 2.5 ms^{-2} and an exposure

maximum limit value of 5.0 ms^{-2}. In order to simplify the exposure calculation from a single period of exposure, has implemented the chart presented in fig. 1 where by knowing the time of exposure and the weighted acceleration the draw of a line "calculates" the partial vibration exposure without the need for calculations (17).

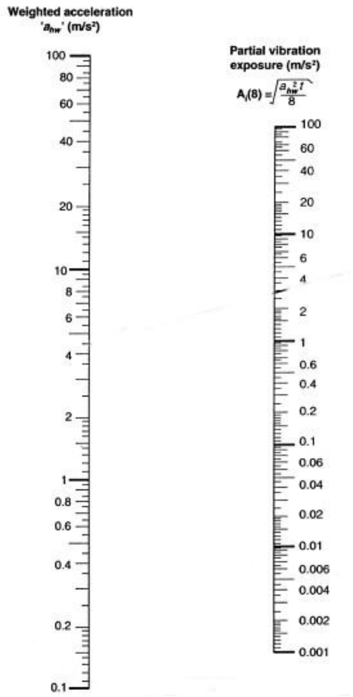

Fig. 1 - HAVS partial exposure calculation chart (17).

Vibration injury to the hands was first reported in 1911 in Italy by Loriga in workers using compressed air tools (13). In 1975 the Taylor-Palmear scale for assessing vibration effect injuries was published. Two alternatives to the Taylor-Palmear scale were introduced in Stockholm in 1987, the vascular scale was subsequently exposed as deficient in that the frequency of blanching attacks is supposed to be used to determine severity. This turned out not to be the case and severity can instead be determined from the results of properly conducted objective vascular tests, such as using a mild cold stress test (water at 20ºC for 1 minute) together with thermal imaging (13). Both scales, like the Taylor-Palmear scale, are entirely subjective.
In 2002 Griffin developed a method of scoring (fig. 2), that can be used to map where blanching symptoms occur. It can be applied to any other type of symptoms that occur in relation with HAVS. The shaded areas correspond to the zones where blanching typically occurs. The author of this map has as-signed a score value to each anatomical region of the fingers to record the severity of the condition (12).

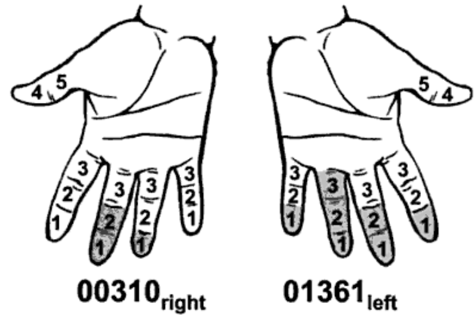

Fig. 2 - Griffin's method of scoring areas of the fingers affected by blanching, (12).

Several clinical and laboratory tests have evolved and became available over the years to assist physicians in evaluating the three components of HAVS. A recent paper, however, concluded that diagnosis and medical tests for HAVS are notoriously crude and can be inaccurate due to clinicians using unsophisticated methods to assess patients (17).
In contrast to this elaborate procedure the already mentioned Italian study that used thermography as a diagnostic technique for assessing vibration injury (1) in conjunction with a study by Bovenzi et al. (4) may offer a faster and more accurate means of diagnosis. Bovenzi concluded that acute exposures to vibration (with equally weighted magnitude) reduces the finger blood flow for all frequencies between 31.5 and 250Hz. While duration of digital vasoconstriction after vibration increases with frequency the constriction severity diminishes: results the study showed that for an exposure time of 2 minutes the frequency with highest reduction of finger blood flow and simultaneously with the shortest recovery time was 31.5Hz.
The aim of this experimental work is to investigate the amount of temperature increase in the hands of healthy controls and subjects presenting early signs, symptoms and clinically confirmed patients of HAVS after holding a vertical vibration device for 2 minutes at a frequency of 31.5Hz.

2. METHODS

2.1 Examination procedure setting

This investigation involved:
- A FLIR A40 (calibrated) thermal camera;
- A PC workstation with CTHERM, MS Excel and SPSS software packages to process and analyse the thermal images;
- A table with a MDF board on top (to improve thermal contrast between limb and background);
- A chair for seating the subject during capture.

• A vibration device (a cinema seat vibration de-vice) as provocation tool, which produces vertical vibration (fig. 3). This type of vibration was suggested by Prof. Griffin in Southampton. This vibration device was isolated with brown paper and plastic (good thermal conductor) to minimize the effect of thermal conductance between the subject and the device.
• A PHILIPS frequency generator set to 31.5 MHz for generating the vibration frequency (fig. 3).
• A PHILIPS frequency counter, to monitor the frequency induced (figure 3).
• A standard GRUNDIG 400W audio amplifier, to amplify the signal from the frequency generator for the vibration device (fig. 3).
• An oscilloscope, to monitor the waveform produced.

The vibration frequency of 31.5Hz frequency was chosen in agreement with literature (4). The induced maximum acceleration from the vibrating device was 36 m/s2, measured by a calibrated laser vibrometer at Swansea Metropolitan University. With the same device the acceleration absorbed by human hands was determined to be 30 m/s2 on average. Using the chart shown in figure 1 and tracing a line from the measured acceleration to the correspondent exposure time of 2 minutes, the partial exposure vibration was found to be 2.5 m/s2, which is half of the maximum allowed by EU regulations (5 m/s2) and was thus considered a safe value for this experiment.

Fig. 3 - The vibration test equipment: on top the vertical vibration motor, underneath the frequency counter, frequency generator and at the bottom the audio amplifier.

A total of 23 subjects participated in this investigation and their characteristics are mentioned in the table 1. They have been divided in 4 groups: the controls (assessed with the EURO-QOL questionnaire with score 0), the signs (which claim the early signs of a condition provocated by using vibration tools), the symptoms (which use vibration handheld tools claim to have at least one symptom of HAVS, however not clinically confirmed) and the HAVS groups (which is composed of medical confirmed patients of the condition).

Table 1. Characteristics of the subjects that participated in this investigation

Group	Gender			
	Males	Females	age	BMI
Controls	5	2	27±8	25±2
Signs	3	4	39±17	25±3.6
Symptoms	1	6	37±8.2	23.2±5.1
HAVS	2	0	49±4.2	27.4±1.5

Posters were used to advertise this study and to ask for volunteers were distributed around the Faculty. Emails were sent to students and staff and an advertisement was posted on the University of Glamorgan intranet website. After volunteers expressed their interest in collaborating in this study, they received information on the experiment and test and were asked to sign an informed consent form.
The HAVS screening questionnaire used in this study is the one suggested and utilised by UK HSE and the NHS (11). Once the volunteers had completed questionnaire and form, their medical his-tory and information on the syndrome relevant for this work could be analysed. Participants were graded and divided into four groups of injury severity based on HAVS signs, symptoms or medical diagnoses according to the guidelines (11).
The thermal camera used in all tests was a FLIR A40 with a resolution of 320x240 pixels, a measurement accuracy (bias, offset) of ±2ºC and a precision (repeatability) of ±0.1ºC. It was connected to a PC using the CTHERM package developed at Glamorgan Medical Imaging Research Unit (14). The lenses used in this imaging system were a standard lens (IR-lens 24º) for regional (close-up) views. All tests were performed in the Thermal Physiology Lab at the University of Glamorgan. All participants while collaborating in the test were constantly monitored for the duration of the test by the author

2.2 Image Capture Protocol

The image capture protocol plays an important role in all infrared imaging investigations, it specifies the subject preparation for the imaging appointment and during the data collection, the room conditions and the capture procedure itself. The recording protocol used in this investigation follows the guidelines of the “Glamorgan Protocol”, which recommends the standard procedures for recording and evaluation of thermal images of the human body (3). It is divided into three sections: the subject, the room and the image recording process.

The subject to be investigated has to follow the following instructions:

- Instructions to be sent to the subject together with the appointment outlining:
  - ◦Avoid smoking for two hours (minimum) before the investigation;
  - ◦ Avoid heavy meals on the day of the examination;
  - ◦Avoid cosmetics and ointments on the skin, these substances act as skin thermal insulators;
  - ◦Avoid physiotherapy or sports on day of the examination;
  - ◦Report infections and any drugs taken, either prescribed by a general practitioner or acquired from a standard pharmacy.

- On arrival:
  - ◦The investigator explains the procedure;
  - ◦The subject completes the needed forms: “Informed Consent”, “Euro-QoL” (the score HAS to be zero for controls), and “HAVS screening questionnaire”;
  - ◦The investigator requests the subject to re-move as much clothing as the volunteer is comfortable with (in changing cubicle) leaving the upper limbs exposed. In actual facts all subjects were wearing either a t-shirt or short sleeved shirt ensuring that the forearms were unclothed;
  - ◦The subject must avoid uneven cooling due to jewellery, crossed legs, or hands/arms placed close or on the body;
  - ◦The investigator has to check the room temperature repeatedly and humidity (temperature has to be 22ºC and humidity below 50% to pre-vent subjects from sweating).

- On scanning:
  - ◦The standard position used is that of both hands in dorsal view as defined in the Glamorgan Standard Capture Protocol (3).
  - ◦A off-the-shelf MDF board has to be used for enhancing the background to hand contrast. The MDF board has a high thermal resistance and therefore does not conduct significant amounts of heat to or from the hands during a single investigation. MDF has, however, a high thermal capacitance so that over time it will assume the temperature of the hands and stay at that temperature for several minutes. In extended or consecutively repeated investigations the board must therefore be replaced with an identical one in order to maintain good contrast and to avoid thermal interference from the previous examination.
  - ◦Marks from tight clothing or seating have to be avoided.
  - ◦No volunteer names/details are stored on any computer system (only a volunteer code is used).This can be cross referenced to the forms which are stored in a locked filing cabinet).

Apart from the member of staff performing the examination, a second member of staff or a person brought in by the participant has to be permanently present in the office area (not the laboratory space itself) as a witness/chaperone.

The examination room has to have a stabilised air conditioning system, that maintains the room tem-perature at 22ºC ± 1ºC and the humidity below 50%. The outside laboratory window has to be completely closed with shutters not only to avoid solar radiation but also to maintain privacy during the examination. An acclimatisation cubicle has to be provided close to the examination room and maintained under the same environmental conditions. The subject can disrobe there and rest for 15 minutes before the exami-nation to facilitate thermal equilibrium. All unneces-sary equipment should be removed from the laboratory area to ensure adequate space for the ex-amination equipment and to avoid thermal reflections. All equipment and the walls have to be away from the subject as far as possible in order to minimise heat reflections. The laboratory area itself should be equipped with the absolute minimum of furniture only to provide adequate room for ma-noeuvre of the equipment and sufficient space between the camera and the volunteer. In order to avoid disturbance during the examination process, a door sign “Examination in progress” should be used.

For the image recording process the investigator has to make sure that all equipment is set up correct-ly (a check list is helpful here). The infrared camera must have been switched on at least 90 minutes be-fore the start of the first capture to avoid start-up drift (15). Before starting the capture process on the subject an image from a calibration source must be taken. The same applies to the end of the process. Both calibration images combined allow the investigator to check for recording errors.

For capturing the desired views from the subject, correct placement in terms of distance, angle to the camera, subject position and field of view of the camera has to be achieved. This adjustment process can be significantly simplified by using capture masks (fig. 4) in the computer capture software which are overlaid onto the live image. Additionally a camera stand (fig. 5), facilitates fast positioning and stable fixation onto the target view.

After capturing the baseline image the volunteer is asked to stand up, hold the vibrating device with the fingertips of the hand maintaining an angle of 90º between arms and forearms. The device was then turned on, inducing the before mentioned vibration frequency of 31.5Hz at an acceleration amplitude of 36 m/s^2 for 2 minutes. After that period the device was turned off and the subject was requested to return to the baseline recording position.

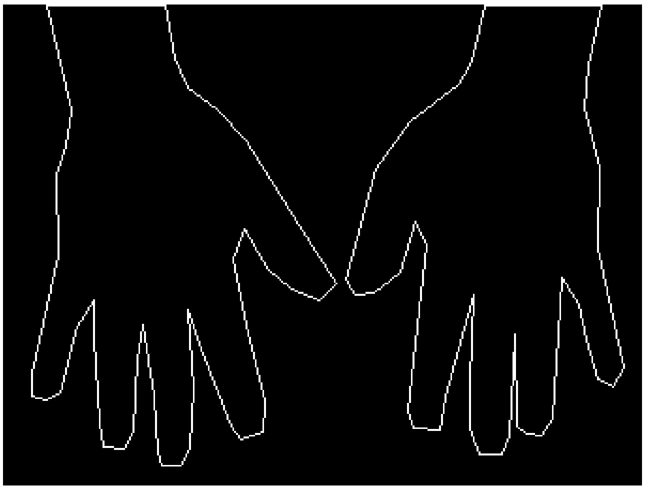

Fig. 4 - Example of a live overlay mask.

Fig. 5 - FLIR A40 IR camera on laboratory stand.

This procedure was immediately followed by a vascular test, where the volunteer is asked to wear a pair of thin latex gloves over the hands and immerse them in a bucket filled with water at 20ºC (monitored by a mercury thermometer). The volunteer remains seated in front of a desk with the hands in a vertical position inside the bucket avoiding contact with the bucket wall or the other hand for a period of one minute. Immediately after this the investigator helps to take off the gloves and makes sure that no direct contact is made with the water. In order to complete the test, the volunteer now places the hands in the recording position (which is the same as the one for taking the baseline image) and for a recovery period of 10 minutes a thermal image is taken at 1 minute intervals. The whole procedure for the case of applying the vascular test only without any pre-provocation is described by the diagram in fig. 6.

For the test, because it involves human subjects, ethical approval was requested and obtained from the Ethics Committee of the Faculty of Advanced Technology at the University of Glamorgan before starting experiment. All individuals collaborating in this research project were treated identically, their confidentiality was respected and no harm was caused to them. All volunteers collaborating in this work could withdraw at any time from the project without being disadvantaged. The author of this work has acted with integrity and has used the available resources as beneficially as possible.

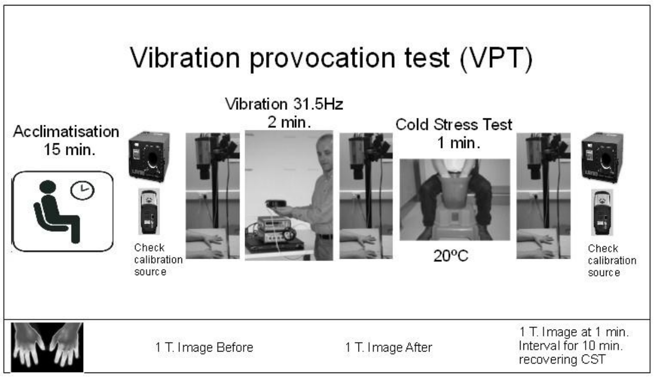

Fig. 6 - The Vibration Provocation Test (VPT) diagram.

3. RESULTS

Observing the right hand Area Of Interest (AOI) (which is based in the model of the hand defined in 18), it can be seen that all the four groups had a decrease of mean temperature, especially the control and confirmed groups. Five minutes after the vascular provocation recovery the greatest negative mean temperature difference was in the control and confirmed groups, the least was indicated by the symptoms group. At the end of the VPT test the greatest negative mean temperature difference was observed in the confirmed group followed by the control group, the symptoms group had recovered

the mean temperature showing the smallest mean temperature difference from baseline (fig. 7).
The left hand AOI as can be observed by fig. 8 only differed from the right hand AOI in the out-come after the VPT test, in this case the signs group presented a minimal higher difference than control group.

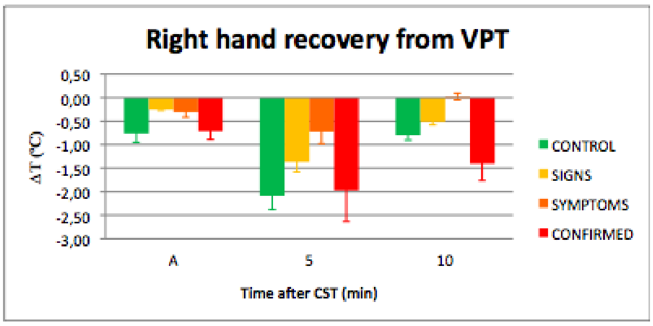

Fig. 7 - Right hand mean temperature difference from baseline when recovering from Vibration provocation test (VPT).

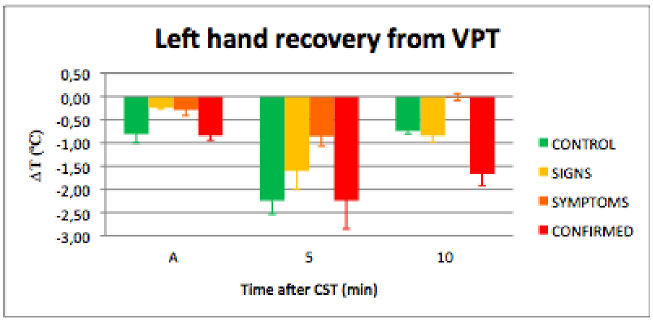

Fig. 8 - Left hand mean temperature difference when recovering from VPT.

In the fig. 9 is shown the variation of mean thermal symmetry (19) difference from baseline over the VPT test. After the vibration expo-sure the value has increased in all groups more significantly in the confirmed group followed by the control group. Five minutes after recovery from vascular challenge the greatest difference was in the confirmed and signs groups. At the end of the VPT test the group presenting the greatest difference was in the signs group closely followed by the confirmed group. The minimal difference was observed in the symptoms group.

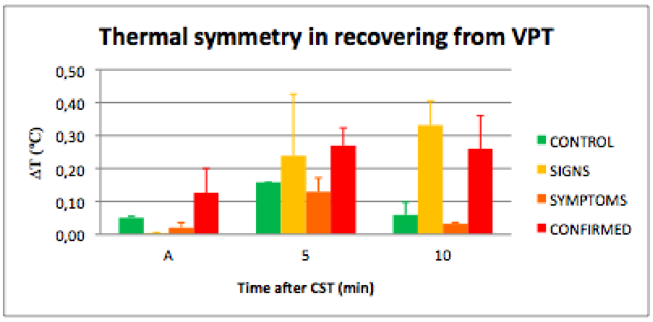

Fig. 9 - Hand thermal symmetry difference from baseline when recovering from VPT.

Observing the mean thermal differences in the index finger DIPs AOI symmetry after the VPT test, it was observed that there was no specific involvement in any particular finger apart from the index in any of the four groups as shown in fig. 10. It can be observed that the confirmed group presented a different pattern than other groups.

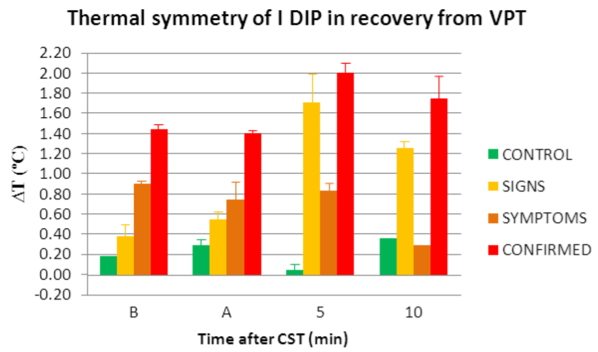

Fig. 10 - Index DIPs thermal symmetry difference when recovering from VPT.

These data have shown that classifying people according to signs rather than symptoms is unreliable.
The fig. 11 presents an example of captured images after being standardised (18), which shows a set of images of a subject from the control group compared with a subject clinically confirmed as having HAVS during a VPT.
Statistical Analysis of the data collected from the VPT test, was obtained a Cronbach Coefficient Alpha for the hand AOI of 0.988, which means good data consistency. The Interclass Correlation Coefficient was of 0.976 with a confidence interval varying from 0.948 to 0.989 demonstrating high reproducibility. The normal distribution of the data was assessed by a K-S test, the p values obtained were 0.515 for the right hand AOI and 0.68 for the left hand AOI. As the K-S test p value > 0.05, it means that the collected data is not different from the normal distribution and the statistical methods associated with this distribution can be used.
A non-parametric Pearson chi-square test was applied between the groups. The result gave a value of 168.000 for the right and left hand AOIs with a significance level inferior to 0.05 (p=0.000 in both AOI). This demonstrates that if their the null hypothesis was true it would be expected to find a x2 value of 168.000 or superior less than 5 times in each 165.000. This rejects the null hypothesis and indicates that the variables are independent. It can therefore be concluded that using thermal images and the VPT test it is possible to identify different HAS stage groups. From the statistical analysis of hypothesis Z-test, there is statistical evidence of

independence between all groups ($p<0.05$) based in both hands AOI.

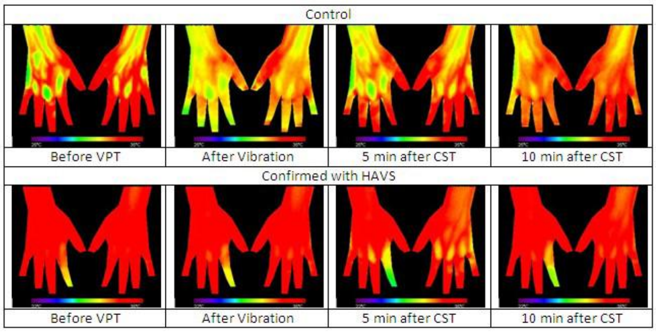

Fig. 11 - An example comparative set of standardised images between a control subject and a clinically confirmed subject with HAVS.

4. DISCUSSION

After vertical vibration exposure for 2 minutes at 31.5Hz all the four groups presented a decrease in mean temperature of the hand in conformity with the literature (2). The application of a vascular provocation test after the vibration exposure produced statistical evidence in mean temperature variation of the hand to discriminate controls from subjects with confirmed symptoms. This procedure significantly differs from most of the published studies in cold provocation testing for HAVS where only a thermal challenge is used (8). These points out the combination of vibration and thermal provocation as objective procedure do provide discrimination between asymptomatic and symptomatic subjects.

The Stockholm scale has not been employed in the classification of subjects in this study. The variation from baseline of thermal symmetry mean value for the four groups during the VPT constituted statistical evidence in the discrimination between healthy controls and confirmed affected symptoms.

There was involvement of the index finger in the subject with confirmed symptoms of HAVS.

The experiment was limited by the sample size available, which limits the weight of conclusions drawn from it.

5. CONCLUSIONS

A standard infrared image capture protocol accompanying a procedure involving mechanical and vascular provocation to the hand was designed, implemented and assessed and is proposed. With the setup described in this publication it is possible to discriminate groups at different stages of the condition, however, for individuals' discrimination a large sample was required, being purposed for future work the implementation in a larger population.

It is also proposed an investigation using the developed methodology, more particularly the thermal symmetry indicator and the proposed campbell's hand injury score system and griffin's havs scoring system to develop an objective and quantitative scale of injury. The purposed methodology of examination could be simplified in exposing mechanically and thermally at same time the subjects to be examined.

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