The Superposition Matrix in Obtaining k-maps for Thermographic Visualization of Rewarming Processes in Hand-Arm Vibration Syndrome

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ABSTRACT: The exposure of workers to hand-arm vibrations remains an important problem in the occupational health. A dynamic thermographic method, proposed for the diagnostics of changes consistent with hand-arm vibration syndrome, involves matrix calculations. The goal of this paper is to present the basics of the mathematical procedures implemented in Mathcad, to obtain the k-maps, which are used as a diagnostic tool for peripheral neurovascular changes.
KEYWORDS: vibration syndrome, k-maps, thermography, superposition matrix, supermatrix

Introduction

In various occupations, exposure of worker's hands to local vibrations is present. These vibrations usually originate from the strongly vibrating power tools (chainsaws, chipping hammers, various grinders etc.) and can cause various types of damage known as the Hand-Arm Vibration Syndrome (HAVS). Disease severity is graded according to subjective neurovascular symptoms which are classified according to the internationally accepted 1986 Stockholm Workshop scale [G+87]. Unlike some of the traditional tests such as those grading the manipulative dexterity or muscle strength (dynamometry), where the subject can influence the results, reliable objective tests are necessary due to scientific, clinical and medico-legal implications.

The objective tests involving measurements of finger skin temperature (FST) and finger systolic pressure (FSP) in response to cold stress (hand immersion in cold water) are most widely used [LH05]. These tests have recently been standardized by ISO [ISO05a, ISO05b]. However, none of the proposed tests so far are completely satisfactory, due to many factors including inter-individual differences in cold response even without occupational exposure to vibrations, the inability of many of the thermometric methods to assess all fingers simultaneously or without introducing perturbations, sensitivity to other confounding factors such as smoking, acclimatization, or even time after the last exposure to vibrations. Thus, a novel method was proposed, using dynamic thermography to generate the k-maps, that is, the visualized distributions of rewarming rates over the volar surfaces of the hands [J+08]. The goal of this paper is to present the basics of the mathematical procedures used to obtain the k-maps, derived from series of thermograms, recorded during the rewarming process after the cold provocation.

1. Methods

The recording system (Fig. 1) consists of an infrared camera connected via RS232 interface to a laptop PC, and a specially designed hand support holding the subject's hand during the recording procedure (Fig. 2).

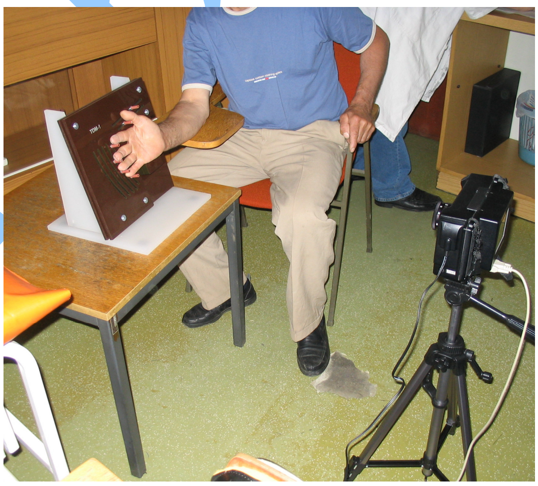

Figure 1. The Recording System

The infrared camera is the Wöhler type IK-21 which detects infrared radiation over the wavelength range from 8 μm to 12 μm and records the thermograms in the 120×120 pixel resolution.

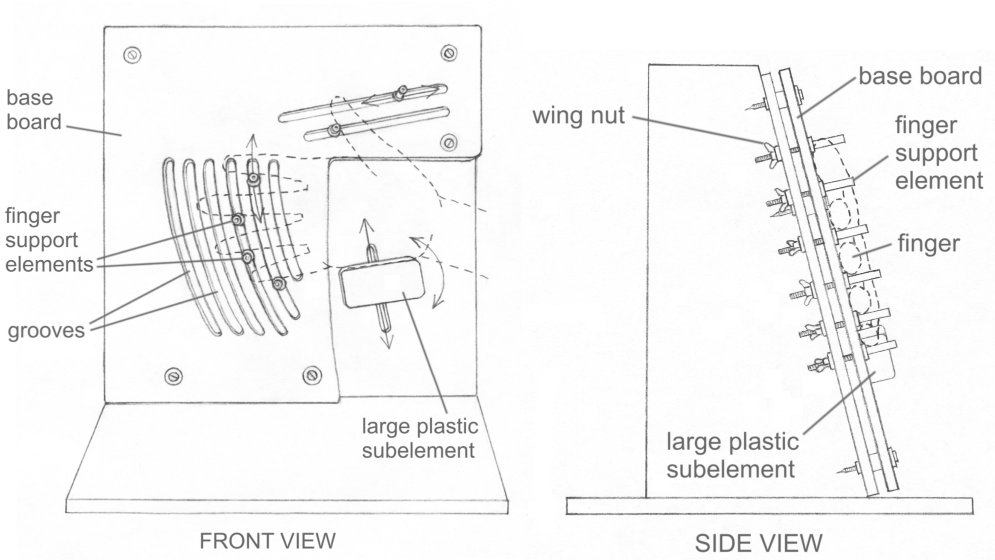

Figure 2. The Hand Support

After the cold provocation in a controlled environment, by immersion of the subject's hand in 8 °C water for 5 minutes, with a latex glove on, the hand is removed from the water and the glove is taken off. The subject sits in a chair with his hand in a specially designed hand support. This ensures the hand to remain stationary during thermographic recording. As explained in [J+08], a sequence of thermograms of the volar side of the hand is recorded during 30 minutes in 30 second intervals. The thermograms thus obtained are used to reconstruct the rewarming process for each pixel individually, producing the temperature data time sequence for each pixel on the volar side of the hand. These data are expected to conform to the exponential law (1) for each pixel [Dup87, F+06, M+02]:

$$T(t) = T_0 + \Delta T(1 - e^{-kt}) \qquad (1)$$

In addition to the series of thermograms recorded during the rewarming phase, a single pre-cooling thermogram is also recorded to correct for the skin emissivity ε and the room temperature.

1. Data Processing and Visualization

The initial data acquisition was performed using the Snapview Pro (ver. 2.1) software and the acquired thermograms were stored as files with the ".isi" extension (ISI files) which is a proprietary file format of Infrared Solutions, Inc. An application was written in the Mathcad environment, for importing, processing and visualization of the recorded data. The data was imported into the application as time series of matrices, each matrix representing a single 120×120 pixel thermogram, each matrix element representing the temperature of the corresponding pixel. The processing uses the data recorded in the following time points: t_1=0 min, t_2=0.5 min, t_3=1 min, ... , t_{21}=10 min, t_{22}=11 min, t_{23}=12 min, ... , t_{26}=15 min, t_{27}=20 min, t_{28}=25 min and t_{29}=30 min. The data is made denser at the beginning of the exponential process, becoming increasingly sparse later. This is done so as to ensure that the data points that represent the later stages of the exponential process would be given less weight in the subsequent fitting procedure. The imported data is, therefore, initially represented as time series of matrices of the form (2).

$$\begin{pmatrix} T_{1,1} & T_{1,2} & \cdots & T_{1,120} \\ T_{2,1} & T_{2,2} & \cdots & T_{2,120} \\ \vdots & & & \vdots \\ T_{120,1} & T_{120,2} & \cdots & T_{120,120} \end{pmatrix} \tag{2}$$

The application then unfolds each matrix of this form into a 14400-element vector. This is done by putting all rows, one after another, into a single row: each next row is added to the right of the previous one, so that finally, a vector of the form (3) is obtained.

$$\begin{pmatrix} T_{1,1} & \cdots & T_{1,120} & T_{2,1} & \cdots & T_{2,120} & \cdots & T_{120,1} & \cdots & T_{120,120} \end{pmatrix} \tag{3}$$

Each of these vectors now represents a single corresponding thermogram, with each of its elements representing the recorded temperature of the corresponding pixel. By superposition of these vectors in the chronological sequence, each new one under the previous, a 29×14400 element superposition matrix (or "Supermatrix") is obtained (4), its *i*-th row being the *i*-th thermogram vector (*i* is marked in the superscript).

The Supermatrix has several convenient features, most important one being that each of its columns represents the time evolution of the temperature of an individual pixel. Thus, referencing the time evolution data for a selected pixel, in a programming environment that supports matrix calculations, is made very simple. The other important feature is the simple procedure employed to obtain the k and R^2 maps (explained later) which, basically, boils down to just folding back the data obtained through fitting, into a matrix, that Mathcad (or some other adequate software), after scaling and normalization, can interpret as a bitmap image to enable visualization.

$$\begin{pmatrix} T_{1,1}^{1} & T_{1,2}^{1} & \cdots & T_{1,120}^{1} & T_{2,1}^{1} & T_{2,2}^{1} & \cdots & T_{2,120}^{1} & \cdots & T_{120,1}^{1} & T_{120,2}^{1} & \cdots & T_{120,120}^{1} \\ T_{1,1}^{2} & T_{1,2}^{2} & \cdots & T_{1,120}^{2} & T_{2,1}^{2} & T_{2,2}^{2} & \cdots & T_{2,120}^{2} & \cdots & T_{120,1}^{2} & T_{120,2}^{2} & \cdots & T_{120,120}^{2} \\ \vdots & \vdots & & \vdots & \vdots & \vdots & & \vdots & & \vdots & \vdots & & \vdots \\ T_{1,1}^{29} & T_{1,2}^{29} & \cdots & T_{1,120}^{29} & T_{2,1}^{29} & T_{2,2}^{29} & \cdots & T_{2,120}^{29} & \cdots & T_{120,1}^{29} & T_{120,2}^{29} & \cdots & T_{120,120}^{29} \end{pmatrix} \quad (4)$$

In order to remove the background pixels, advantage is taken of the fact that the temperature of the "live" pixels (corresponding to the subject's hand) exhibit large difference between the initial and final stage of the rewarming, compared to the "dead" ones in the background. Hence, the software calculates the difference between the final and initial temperature, for each pixel. A threshold value for the difference is set by user, and all pixels not exceeding the preset value are represented as black (background). This is facilitated by the fact that the room temperature needs to be controlled in order to obtain reproducible results, so the background temperature variance is minimal. There is, thus, a large span of threshold values that a user can select and obtain good results. It should be chosen as small as possible, to remove the background pixels: as a result of practical experience, we selected and kept the cutoff value of 5 °C, which proved adequate for most of the cases. It is important to note that selecting smaller cutoff values adds a few more pixels (mostly around the hand, or in the background) but does not change their corresponding k-values (this parameter only changes the number of "live" pixels, i.e. the pixels for which the k-values are calculated, and it affects the overall look of a k-map, but not the calculated k-values in "live" pixels). Some advanced techniques employ also the pixel temperature obtained from the pre-cooling thermogram, but these are beyond the scope of this paper.

Only the "live" pixels, i.e. their corresponding columns of the Supermatrix, are retained for further processing. The data from each of the "live" columns is fitted to the relationship (1) using the Levenberg-Marquardt method for minimization, producing the parameters k and ΔT. These are stored in two additional rows of the Supermatrix. The coefficient of determination R^2 is also calculated, and stored in its own additional row. The processing, thus, produces a corresponding set of these values for each of the "live" pixels, using curve fitting through the recorded temperature data points.

As the value k quantifies the dynamics of the rewarming process (i.e. greater k implies more rapid rewarming), it is useful to produce a “k-map”, that is, to visualize the spatial distribution of this parameter over the area of the volar side of the hand, in a similar manner as the “Tau image” was produced in earlier works [8]. This is facilitated by virtue of the fact that the Supermatrix row, containing the k value data, already represents the spatial k value distribution, in the form of a vector, as in (3). This data is just to be read and folded back into 120 rows of pixels, producing a 120×120 k-matrix. Converting this data into the RGB format, and using the Ironbow palette, visualization is made easy. Gray color is reserved for visualization of R^2 distribution: regions with low R^2 values indicate unsuccessful exponential fit, which warrants further investigation.

An example recorded k-map of a healthy individual is shown in Fig. 3. Warmer colors correspond to higher values of k (faster rewarming rates), while colder colors correspond to slower rewarming. The higher rewarming rates in the distal finger regions are typically found in healthy subjects.

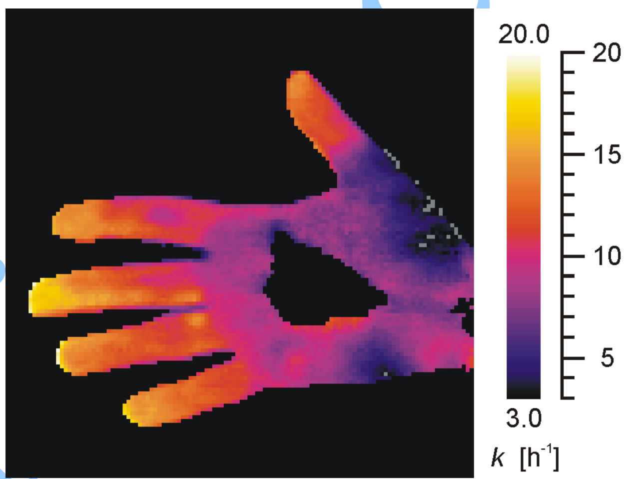

Figure 3. An Example k-map of a Healthy Individual

2. Weighted k Values

The application of the proposed method in some cases reveals that, even though the calculated rewarming rates (k values) are relatively high, the subject's hand temperatures fail to return to pre-cooling values within 30 minutes. This leads to a conclusion that the temperature change ΔT, observed during rewarming, should also be included in some way in the final descriptor of the dynamics of a rewarming process in those cases. For this purpose, the k alone is not sufficient. Referencing back to Eq. (1), we see that the $k\Delta T$ product is equal to the first derivative of temperature $T(t)$ with respect to time, at the beginning of a rewarming process ($t = 0$):

$$\left.\frac{d\,T(t)}{d\,t}\right|_{t=0} = k\Delta T \quad (5)$$

Hence, $k\Delta T$ is a measure of the initial rate of temperature recovery. It is, therefore, suggested to introduce the product of the calculated k value and the measured temperature change ΔT for a given pixel as a new parameter, named "weighted k value" for those cases. This parameter incorporates both the rate of the temperature recovery and its actual change. In addition, the calculation of the weighted k values is fairly simple since the corresponding k values and the measured temperature changes ΔT are both immediately available. Visualization of these values is made in the same way as with the k values, producing a "weighted k-map".

Conclusions

The observations and parameters, related to the rewarming after the cold provocation by hand immersion in cold water, are included in a number of commonly used diagnostic procedures in occupational health, for thermometric examination of the fingers in workers exposed to hand-arm vibrations. Contact thermometry or, to a lesser degree, thermography are used. However, except for the works of Merla et al. [M+02], very little was done to develop dynamic thermographic procedures which utilize all of the available rewarming data and quantify the dynamics of the rewarming process rather than simply use the parameters derived from it. Thermography offers the opportunity to examine all the affected fingers simultaneously, and the dynamic thermography is different from the static one in that it uses and visualizes the parameters describing the rewarming rate, rather than just the distribution of temperature at a given moment.

The mathematical procedure involving a Supermatrix is a convenient one when a software package capable of matrix calculations is used. In order to avoid the complex software corrections due to movement artifacts, the special hand support had to be designed to hold the subject's hand in place during the recording. While the Mathcad application, and the corresponding mathematical apparatus were developed for the investigation of HAVS cases, it can also be implemented whenever a parameter (or a set of parameters) quantifying the rewarming rate over the investigated area is to be visualized.

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