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An integrated approach to whole-body vibration

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Abstract

The objective of this thesis is to determine and quantify the effects of whole-body vibration to the human body in terms of energy expenditure, by means of a global and integrated approach. This objective is attained by considering the human body as a complex organic structure. In order to understand how it responds to vertical vibrations, the energy expenditure of the human body was measured by means of the variation in superficial temperature with the aid of infrared thermography, the displacement of the muscles with the aid of the Vicon MX motion analysis system and the oxygen uptake with the aid of the Cosmed K4 telemetric system. The establishment of an appropriate protocol which satisfies the aim of this study was the first goal. The lack of consistency in whole-body vibration protocols in the current published studies makes the establishment of an appropriate protocol essential, and in this sense, an experiment setup was implemented. Therefore, a series of experiments was conducted to examine the response of the human body to vertical vibrations, changing the duration and the frequency of vertical vibration, and the duration of rest period. A number of four persons were subjected to vertical vibrations on a vibrating table in a standing position at a frequency ranging from 20 to 50 Hz. After the establishment of the final protocol, a series of laboratory experiments took place. Three different vibration frequencies were chosen: 20, 30 and 45 Hz corresponding to three different tests. The most interesting findings regard the oxygen consumption, the superficial temperature evolution, and the transmissibility coefficients for the acceleration.

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Sommario

Obiettivo di questa tesi è la determinazione e quantificazione degli effetti della whole-body vibration al corpo umano, in termini di consumo energetico, tramite un approccio globale e integrato. L'obiettivo è ottenuto considerando il corpo umano come una struttura organica complessa. Allo scopo di comprendere come questo risponda alle vibrazioni verticali, il consumo energetico del corpo umano è stato misurato per mezzo della variazione della temperatura superficiale con tecniche di misurazione a termografia infrarossa. Lo spostamento dei muscoli invece con il sistema di analisi di movimento Vicon MX. Infine, per quanto riguarda il consumo di ossigeno con il sistema telemetrico Cosmed K4. Il primo passo è stato l'istituzione di un protocollo appropriato che soddisfi l'obiettivo di questo studio. Infatti, la mancanza di coerenza nei protocollo di whole-body vibration che si trovano allo stato dell'arte, ha reso essenziale l'istituzione di un apposito protocollo, ed a questo scopo è stata definita la struttura dell'esperimento. Di conseguenza, è stata avviata una serie di prove per esaminare la risposta del corpo umano alle vibrazioni verticali, cambiando la durata e la frequenza della vibrazione, nonché la durata del periodo di riposo. In totale, quattro persone in piedi sono state sottoposte a vibrazioni verticali, in una pedana vibrante, a frequenze da 20 a 50 Hz. Dopo l'instaurazione del protocollo finale, sono stati avviate una serie di prove di laboratorio. In particolare, sono state scelte tre frequenze per le vibrazioni: 20, 30 e 45 Hz. I risultati ottenuti più interessanti di questo studio, riguardano il consumo di ossigeno, la temperatura superficiale e i coefficienti di trasmissibilità dell'accelerazione.

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CHAPTER 1

Introduction

The human body is exposed on a daily basis to different kind of vibrations, transmitted by different parts into the body, e.g., in vehicles, in aircrafts, by hands, feet, backside etc. Thus whole-body vibrations occur when the human body (either when standing, lying or being seated) is in contact with a vibrating surface. The body depends on a range of structures and mechanisms to regulate the transmission of vertical vibrations through the body itself, including: bones, cartilage, synovial fluids, soft tissues, joint kinematics and muscular activity. Therefore, human response to whole-body vibration is a very complex phenomenon.

In the last decades many studies have been conducted to investigate the effect of whole-body vibration exposure. In particular, several extensive studies have been conducted to summarize the effects of vertical vibration on the human body and it can be concluded that responses are diverse [1 - 6].

There is ample evidence accumulated over the last 30 years, both in studies contacted to animals and humans that prolonged exposure to vibration can result in bodily damage. Vibration has been studied extensively for its dangerous effects on humans at specific amplitudes and frequencies. Prolonged exposure to vertical vibration has been shown to induce fatigue and to inhibit neuromuscular performance [7, 8]. Several studies have shown an association between exposure to seated whole-body vibration and low back pain [9 – 11].

On the other hand, studies showed the beneficial effects of vertical vibrations and reported that whole-body vibration has positive effects on improving the performance of an athlete, on the energy metabolism and on the blood flow. Recent studies suggest that low amplitude, low frequency mechanical stimulation of the human body is a safe and effective way to exercise musculoskeletal structures. Trovinen et al. [12] have suggested that short-time exposure to whole-body vibration could lead to an improvement in vertical jump performance and force generating capacity in the lower limbs. Lebedev et al. [13] showed that vibrations could extract excitatory inflow through muscle spindle motoneurons connections in the overall motoneuron inflow. In addition, many studies have shown that there is a strong connection between whole-body vibration and acute responses of hormonal profile and neuromuscular performance. Bosco et al. [14] suggested that there is a significant increase in the plasma concentration of testosterone and growth hormone, whereas cortisol levels decreased. That means that whole-body vibration elicit a biological adaptation. In addition, Kerschan-Schindl et al. [15] showed that high frequency vibration could have negative effects on blood flow and muscle strength while low frequency vibration increased the mean blood flow velocity in the popliteal artery and reduced resistive index of blood flow velocity.

Vibration exposition may have also potential in preventing and treating osteoporosis by means of a direct vertical stimulus to the skeletal structure of the human body, with the direct consequence the stimulation of the cells responsible for producing a higher bone mineral density.

From the above finings and considerations it is evident that exposure to whole-body vibration is not a panacea. This is more truth considering that the human body is a complex structure, and each individual may behave differently when subjected to the same stimulus. Negative and positive effects have to be accounted for and evaluated on a case by case basis, considering the specific conditions (e.g. vibration duration and amplitude). Eventually, in case of an application to an individual, a trade-off between positive and negative effects has to be made, based on more or less reliable assumptions.

1.1 Thesis Focus

In this thesis the standing human body exposed to vertical vibration is examined and the energy expenditure of the human body in a vibration environment is estimated. In particular, the oxygen uptake, the displacement of the muscle and the variation of the superficial temperature are calculated and compared for different vibration frequencies and different time of vibration exposure.

The principal aim was to investigate on the goodness of implementing a global approach to whole-body vibration. In a first place, since it was found that there is confusion to some extend about the whole-body vibration protocols, an appropriate whole-body vibration protocol has been developed and implemented, in order to study the effects of whole-body vibration to the human body in a standing position. In particular a series of experiments was conducted in this study, changing the duration of vertical vibration, the frequency of vertical vibration and the duration of the rest period.

Consequently, after the establishment of the final protocol, a series of experiments took place in a laboratory. It was possible to assess the energy expenditure of the human body in a vibration environment by means of a global and integrated approach. In particular, the oxygen uptake, the variation of the superficial temperature and the displacement of the muscles were calculated and compared for three different vibration frequency values.

1.2 Thesis Outline

The remainder of this thesis is outlined as follows:

Chapter 2 is an introduction to the mechanics of vibration, divided into four phases: classification of vibration, magnitude and frequency of vibration and instruments used for the measuring of vibration.

Chapter 3 describes the thermoregulation in the human body and the interaction between the human body and the environment for what concern the transfer of heat. The factors influencing the thermoregulation of the human body are also described.

Chapter 4 describes the heat transfer mechanisms of the human body.

Chapter 5 provides a comprehensive review of the evolution of the heat exchange equation and of the three models which characterize this equation.

Chapter 6 connects the energetic consumption with a mathematical model. The Sacripanti model is described and how it has been improved for the purpose of this research.

Chapter 7 is dedicated to the whole-body vibration. An introduction of the mechanics of whole body vibration is given and important concepts are described, such as the concepts of vibration axes, frequencies and magnitudes and the duration of the whole-body vibration. The beneficial effects of vibration and the health and comfort problems caused by vibration are also described.

Chapter 8 describes the indirect measurements of the human whole-body vibration and the mechanical models of the human body that can be used to study the response of the human body to whole-body vibration.

Chapter 9 describes the mechanical parameters of the vibrating table. The response of the vibrating table used for this thesis in a specific range of frequencies is also given.

Chapter 10 describes the systems used for the acquisition and elaboration of the data. The Vicon MX Motion System, the Cosmed K4 telemetric system and the infrared thermography system are described.

Chapter 11 provides a review of the pre-analysis in order to find an appropriate protocol for this research. The experimental set-up and the final protocol are described.

Chapter 12 provides the concluding results of the experiments, regarding in particular the motion capture, the oxygen uptake and the thermography.

Chapter 13 summarizes the conclusions and the findings and provides some suggestions for further research.

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CHAPTER 2

Mechanics of vibration

A vibration, in its simplest form, can be considered as the oscillation or the repetitive motion of an object around a position of equilibrium. The equilibrium position is the position the object will attain when the excitation force acting on it is zero. The extent of the oscillation determines the magnitude of the vibration and the repetition rate of the cycles of oscillation determines the frequency of the vibration.

The vibratory motion of a whole body can be completely described as a combination of individual motions of six different types. These are translation in the three orthogonal directions x, y, and z, and rotation around the x, y, and z-axes. Any complex motion the body may have can be broken down into a combination of these six motions. Such a body is therefore said to possess six degrees of freedom.

2.1 Classification of vibration

The vibration of an object is always caused by an excitation force. This force may be externally applied to the object, or it may originate inside the object. The frequency and magnitude of the vibration of a given object is completely determined by the excitation force, direction, and frequency.

It is possible to distinguish two types of excitation functions, namely, deterministic and nondeterministic, where the latter is also known as random. Deterministic functions may be further subdivided in harmonic, periodic and non periodic (also known as transient).

The common characteristic of the deterministic functions is that their values can be determined for any future time t. The response of systems to deterministic excitations is also deterministic. There are many physical phenomena, however, that do not lend themselves to explicit time description. The implication is that the value at some future time of the variables describing these phenomena cannot be predicted. Phenomena whose outcome at a future instant of time cannot be predicted are classified as nondeterministic and referred to as random. A typical example of such phenomena is the jet engine noise. The response of a system to random excitation is also a random phenomenon. In such cases it is more feasible to describe the excitation and response in terms of probabilities of occurrence than to seek a deterministic description [1].

Vibration exposures encountered during work, travel and leisure are often described as random. For a “stationary” random vibration a sample averaged over a sufficiently long period is independent of the period of time over which the sample was taken. Some experimental studies with sinusoidal and stationary random vibration have investigated whether human response to random vibration can be predicted from a knowledge of response to sinusoidal motion. A knowledge of the outcome of such studies is necessary before the results of sinusoidal studies can be applied to random vibration environments [2].

Methods proposed for the evaluation of human vibration exposures have usually assumed that the motion is stationary and that a representative average value can be used to indicate the severity of the motion over the full period of exposure. In practise, of course, the vibration conditions often change from moment to moment. Restricting the evaluation of vibration to periods when the motion is stationary may exclude the periods of greatest interest. If a motion is translational a rigid body oscillate and all its parts undergo the same motion. If the motion is rotational a rigid body rotates and in this case not all of its parts undergo the same motion. Both translational and rotational vibration influence human responses.

2.2 Vibration magnitude

Vibration is defined by its magnitude and frequency. There are many possible means by which the magnitude of an oscillatory motion can be measured. The magnitude of vibration could be expressed as the displacement. The displacement is simply the distance from a reference position, or equilibrium point. When the motion is harmonic, the displacement *x(t)* is:

$$x\left(t\right) = X \sin 2\pi ft \qquad (1)$$

where:

X = maximum displacement amplitude in metres

f = frequency (cycles/second) in hertz (Hz)

π = constant 3.1416

t = time

The magnitude of vibration may alternatively be defined by the velocity, which is more directly related to the energy involved in the movement. The velocity of a vibrating object refers to the time rate of change of displacement and is expressed as:

$$v = \frac{dx}{dt} = V \cos 2\pi ft \qquad (2)$$

where $V = 2\pi fX$

However, most vibration transducers produce an output that is related to acceleration (their output is dependent on the force acting on a fixed mass within the transducer and, for a fixed mass, force and acceleration are directly related). The acceleration *a(t)* of an object refers to the time rate of change of velocity and is expressed as:

$$a(t) = \frac{dv(t)}{dt} = \frac{d^2x(t)}{dt^2} = -A\sin 2\pi ft \qquad (3)$$

where $A = 2\pi fV = (2\pi f)^2 X$

The displacement of a body undergoing simple harmonic motion is a sine wave. It also turns out that the velocity of the motion is sinusoidal. When the displacement is at a maximum, the velocity will be zero because that is the position at which its direction of motion reverses. When the displacement is zero (the equilibrium point), the velocity will be at a maximum. This means that the phase of velocity waveform will be displaced to the left by 90 degrees compared to the displacement waveform. In other words, the velocity is said to lead the displacement by a 90-degree phase angle.

Remembering that acceleration is the rate of change of velocity, it can be shown that the acceleration waveform of an object undergoing simple harmonic motion is also sinusoidal, and also

that when the velocity is at a maximum, the acceleration is zero. In other words, the velocity is not changing at this instant. Then, when the velocity is zero, the acceleration is at a maximum – the velocity is changing the fastest at this instant. The sine curve of acceleration versus time is thus seen to be 90 degrees phase shifted to the left of the velocity curve, and therefore acceleration leads velocity by 90 degrees.

These relationships are shown in Fig. 1 where the acceleration is 180 degrees out of phase with the displacement. This means the acceleration of a vibrating object is always in the opposite direction to the displacement. The preferred S.I. unit for quantifying acceleration magnitude is metres per second per second (ms^{-2}).

A vibration signal plotted as displacement vs. frequency can be converted into a plot of velocity vs. frequency by a process of differentiation. Differentiation involves a multiplication by frequency, and this means the vibration velocity at any frequency is proportional to the displacement times the frequency. For a given displacement, if the frequency is doubled, the velocity will also double, and if the frequency is increased tenfold, the velocity is also increased by a factor of ten. In order to obtain acceleration from velocity, another differentiation is required, and this results in another multiplication by frequency. The result is that for a given displacement, the acceleration is proportional to the frequency squared. This means that the acceleration curve slopes upward twice as steeply as the velocity curve.

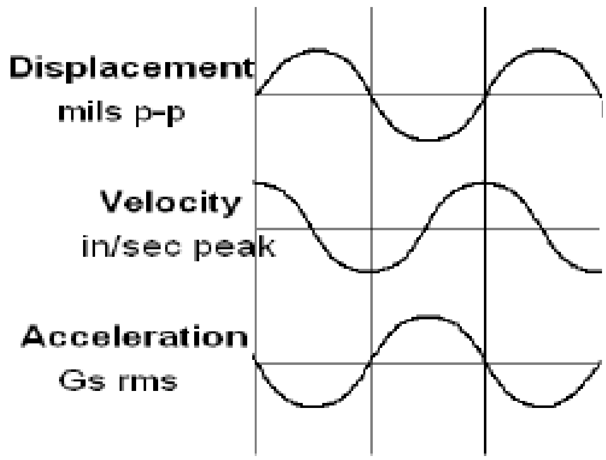

Figure 1 Displacement, velocity and acceleration of a vibrating body.

The acceleration magnitude of a vibration could be expressed in terms of the peak-to-peak amplitude or the peak amplitude. The peak amplitude (*Pk*) is the maximum excursion of the wave from the zero or equilibrium point and the peak-to-peak amplitude (*Pk-Pk*) is the distance from a negative peak to a positive peak. In the case of the sine wave, the peak-to-peak value is exactly twice the peak value because the waveform is symmetrical, but this is not necessarily the case with all vibration waveforms.

Since with complex motions this may result in the severity of the vibration being determined by one unrepresentative peak, it is often preferred to express severity in terms of an average measure. The measure in greatest use in engineering is the root-mean-square (r.m.s.) value (Eq. 4) which is the square root of the average of the squared values of the waveform (see Fig. 2).

$$a_w = \left[\frac{1}{T} \int_0^T a_w^2(t)\,dt \right]^{\frac{1}{2}} \qquad (4)$$

where:

w = weighting factor for different conditions

$a_w^2(t)$ = instantaneous frequency-weighted acceleration

T = integration time for running averaging

In the case of the sine wave, the r.m.s. value is 0.707 times the peak value, but this is only true in the case of the sine wave. The r.m.s. value is proportional to the area under the curve. Root-mean-square acceleration (i.e. ms^{-2} r.m.s.) is generally adopted as the preferred method of quantifying the severity of human vibration exposures. The preference is not based on any fundamental reasoning that r.m.s. measures of acceleration should predict any human response more accurately than peak-to-peak, peak or any other measure. The prime justification is the convenience of measurement and analysis and the harmonization with some other areas of engineering [2].

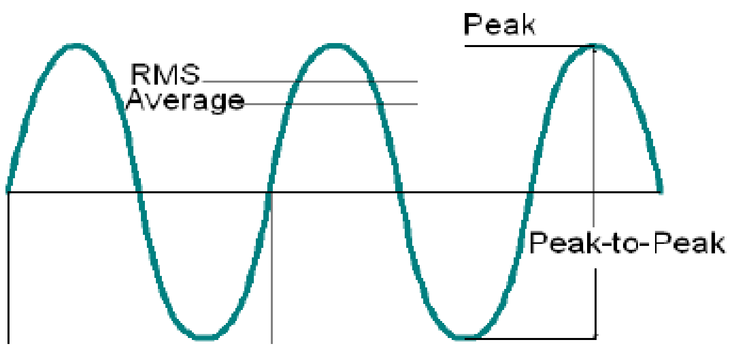

Figure 2 Peak-to-peak amplitude, peak amplitude and root-mean-square**.**

For real-world exposures in which the vibration characteristics vary greatly from moment to moment, the period over which the r.m.s. magnitude should be determined is not always apparent and the r.m.s. value can sometimes be shown to be an inappropriate measure. A simple measure sometimes used to indicate the conditions where r.m.s. and peak values are not appropriate is the ratio of the peak value to the r.m.s. value of the vibration:

$$Crest\ factor = \frac{peak\ acceleration}{RMS\ acceleration} \tag{5}$$

The crest factor is a dimensionless quantity. In a perfect sine wave, with an amplitude of “1”, the r.m.s. value is equal to .707, and the crest factor is then equal to 1.41. A perfect sine wave contains no impacting and therefore crest factors with a value higher than 1.41 imply that there is some degree of impacting. The use of the crest factor implies that for low crest factor motions human response is reasonable indicated by the r.m.s. value while for high crest factor motions it is mainly determined by the peak value. A single measure applicable over all crest factors should therefore asymptotically approach the characteristics of these two measures with extreme crest factors [2].

Griffin [2] presented crest factors for some vehicles. In a car the crest factors varied between 4.7-5.5 whereas for a van the crest factors varied between 4.1-20.0. For tractors the crest factors varied between 3.6-12.8 and for tanks between 3.6-21.2. The highest crest factors were found in the z-direction for all vehicles. Thus, high crest factors are existent also in other types of vehicles.

2.3 Vibration frequency

The time it takes each point in question to make a complete oscillation is called a cycle of motion or period (*T*) which is reported in seconds. The frequency is simply the reciprocal of the period (Eq. 6). The unit for frequency is hertz (Hz) named after the German scientist Heinrich Hertz. One hertz means one cycle per second.

$$f = \frac{1}{T} \tag{6}$$

Simple harmonic motion occurs when there is a sinusoidal oscillation at a single frequency. This is the simplest type of motion since it contains only one frequency. In reality, vibration exposure is non-sinusoidal but can be represented by a combination of sinusoidal components having appropriate amplitudes, frequencies and phases.

Another important concept in the mechanics of vibration is the phase. Phase is a measure of relative time difference between two sine waves. Even though phase is truly a time difference, it is almost always measured in terms of angle, either degrees or radians. This represents normalization to the time taken by one cycle of the wave in question, without regard to its true time period. The phase difference between two waveforms is often called a phase shift. A phase shift of 360 degrees is a time delay of one cycle, or one period of the wave, which actually amounts to no phase shift at all. A phase shift of 90 degrees is a shift of 1/4 of the period of the wave, etc (Fig. 3). Phase shift may be considered positive or negative, i.e., one waveform may be delayed relative to another one, or one waveform may be advanced relative to another one. These conditions are called phase lag and phase lead respectively.

The phase angle can be measured from the reference position either in the direction of rotation or opposite to the direction of rotation, i.e., phase lag or lead, and different equipment manufacturers use different conventions.

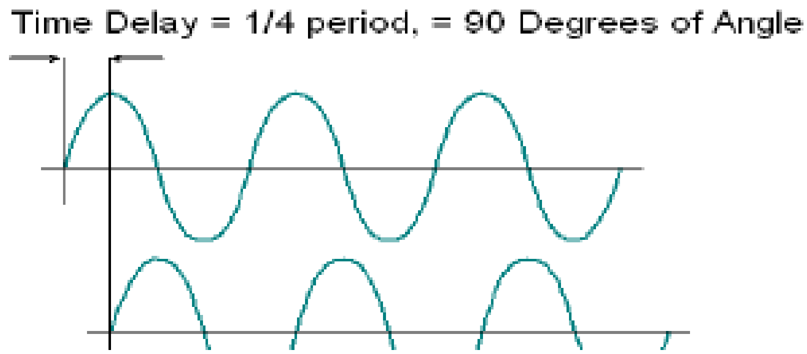

Figure 3 The phase shift between two waveforms.

Theoretically, waves can extend forever. Realistically, they are limited by the size of the system. Boundaries create conditions that favour special frequencies or wavelengths. Just as the length of the string set the period of the pendulum, the boundaries and properties of the system make certain waves much more powerful than others. The concepts of resonance and natural frequency apply to a huge range of natural and human-made systems. These two powerful ideas are the key to understanding the tides of the ocean, the way our ears separate sound, and even how a microwave oven works.

Natural frequency is the frequency at which a system naturally vibrates once it has been set into motion. In other words, natural frequency is the number of times a system will oscillate (move back and forth) between its original position and its displaced position, if there is no outside interference. Microwave ovens, musical instruments, and cell phones all use the natural frequency of an oscillator to create and control waves. Musical instruments work by adjusting the natural frequency of vibrating strings or air to match musical notes. The a string on a guitar has a natural frequency of 440 Hz.

Resonance is the tendency of a system to oscillate at maximum amplitude at certain frequencies, known as the system's resonance frequencies (or resonant frequencies). At these frequencies, even small periodic driving forces can produce large amplitude vibrations, because the system stores vibrational energy. Resonance can be either desirable or undesirable. Acoustic resonance, a desirable resonance, occurs in many different musical instruments. It also occurs in auditoriums. Undesirable mechanical resonance can cause bridges to collapse, aircraft wings to break, and machinery to break or malfunction. For example, the Tacoma Narrows Bridge experienced large vibration amplitudes and catastrophic structural failure due to wind gusts.

The natural frequency depends on many factors, such as the tightness, length, or weight of a string. We can change the natural frequency of a system by changing any of the factors that affect the size, inertia, or forces in the system. For example, tuning a guitar changes the natural frequency of a string by changing its tension.

Any physical structure can be modelled as a number of springs, masses, and dampers. Dampers absorb energy, but springs and masses do not. A spring and a mass interact with one another to form a system that resonates at their characteristic natural frequency. If energy is applied to a spring-mass system, it will vibrate at its natural frequency, and the level of the vibration depends on the strength of the energy source as well as the absorption or damping inherent in the system. The eigen frequencies and damping ratio of an original suspension (where there is one) has to be calculated. Afterwards, possible improvements can be evaluated. The eigen frequency, f_0, of a mass damper system is calculated using the following equation:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \qquad (7)$$

where:
f_0 = the natural frequency
K = the spring constant or stiffness (N/m)
M = the mass (kg)

From this, it is seen that if the stiffness increases, the natural frequency also increases, and if the mass increases, the natural frequency decreases. If the system has damping, which all physical systems do, its natural frequency is a little lower, and depends on the amount of damping.
The K can be non-linear, i.e. changing value according to load (compression).
The damping ratio, ζ is calculated from the critical damping, C_c (N/ms), and the damping coefficient C (N/ms) of a damped suspension system by Eq. 8:

$$\zeta = C / C_c \qquad (8)$$

Where the critical damping, C_c, is calculated by Eq. 9:

$$C_c = 2\sqrt{(K \cdot M)} \qquad (9)$$

where M is the mass (kg) and K (N/m) is the stiffness.

The transmissibility may be calculated as follows:

$$T_F = \sqrt{\frac{1+(2\zeta X)^2}{(1-X^2)^2+(2\zeta X)^2}} \quad (10)$$

where T_F is the transmissibility and $X = f/f_0$

Transmissibility is used to describe the response of a vibration isolation system. Literally, transmissibility is the ratio of displacement of an isolated system to the input displacement. It is used to describe the effectiveness of a vibration isolation system.

The acceleration and transmissibility in a single mass damper system (Fig. 4c) is shown in Figs. 4a - 4b for four different damping ratios, ζ: 0.0, 0.2, 0.5 and 1.0, which affect the attenuation of the vibration magnitude. There are three categories of damped motion: $\zeta>1$ (over damped), no oscillations: $\zeta=0$ (no damping), no attenuation of oscillations; $\zeta<1$ (under damped), oscillations occur.

The four different damping ratios; $\zeta=0.0$ (no damping), $\zeta=0.2$, $\zeta=0.5$, and $\zeta=1$ (critically damped), illustrate the attenuation of the vibration magnitude in Fig. 4. The oscillations for the four different damping ratios are shown in Fig. 4a. Also, the transmissibilities as functions of the ratio of the frequency of the vibratory force to the resonance frequency of the system are shown in Fig. 4b.

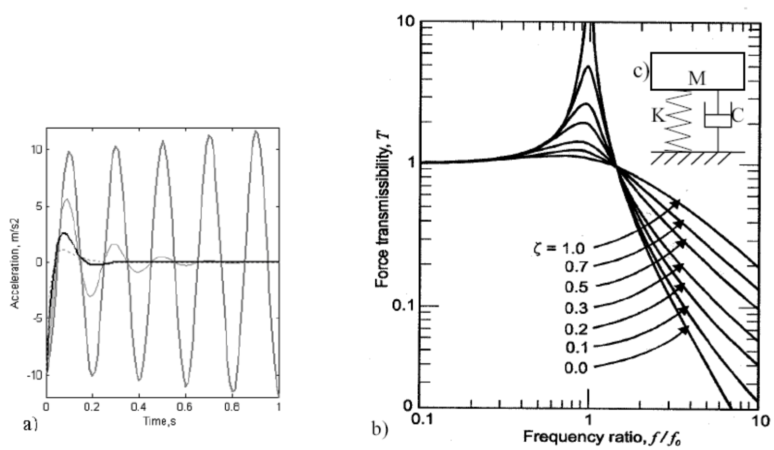

Figure 4 The acceleration vs. time (a) and the force transmissibility, T_f, vs. frequency ration for four damping ratios (b) where $\zeta=0.0$ (thick solid grey line), $\zeta=0.2$ (thin solid grey line), $\zeta=0.5$ (solid black line) and $\zeta=1$ (dashed grey line). The conditions of the mass damper system (c) are M=10 kg; K=9869.6 N/m (which corresponds to $f_0=5$ Hz), the length of the spring is 100 mm and the initial velocity is 0 km/h.

Moving the peak of the eigen frequency, f_0, to left or right decreases or increases the stiffness of the mass damper system in Fig. 4. In case of the forklift, it can affect the assessed vibration discomfort since humans are more or less sensitive to different frequencies. The magnitude of the eigen frequency, f_0, can be attenuated by a damper, especially if the eigen frequency is found to be in a frequency range where humans are sensitive. When the damping ratio is increased as in Fig. 4c it attenuates the vibration magnitude at f_0 but magnitudes at higher frequencies increase. Since a transient consists of high frequencies, a damping ratio close to 1.0 gives rise to a higher peak amplitude

2.4 Vibration measuring instruments

The basic element in most vibration measuring instruments is the seismic unit as shown in Fig. 5. The most common vibration measuring instruments are used to measure displacement and accelerations. Many instruments consist of a case containing a mass-damper-spring system and a transducer measuring the displacement of the mass relative to the case. The motion of the mass is converted in to an electrical signal by the vibration transducer. The transducer transforms changes in mechanical quantities such as displacement velocity, acceleration in to changes in electrical quantities such as voltage or current. Since the output signal of a transducer is too small to be recorded directly, a signal conversion instrument is used to amplify the signal to the required value (amplifier). The output from the signal conversion instrument can be displayed on a display unit or stored in a computer for later use. Modern vibration measurements employ transducers which convert mechanical energy into electrical energy.

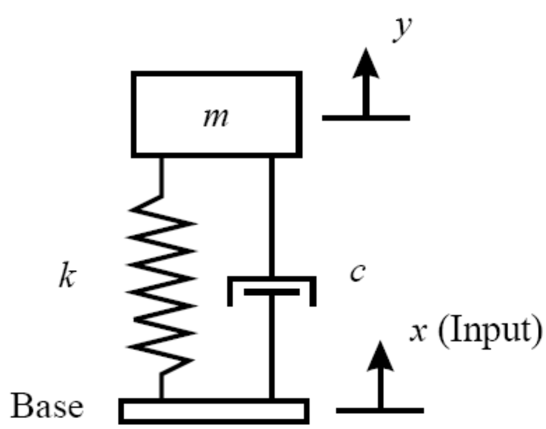

Figure 5 The seismic unit.

The equation of motion of the mass is:

$$m\ddot{y}+c\left(\dot{y}-\dot{x}\right)+k\left(y-x\right)=0 \qquad (11)$$

where y and x are the displacement of the seismic mass and the vibrating body, respectively. Both of these displacements are measured with respect to an inertial reference. Let z be the relative displacement of the mass and the vibrating body, i.e. $z = y - x$, we can rewrite Eq. 11 as :

$$m\ddot{z} + c\dot{z} + kz = -m\ddot{x} \tag{12}$$

For sinusoidal measurements $x = X\cos\omega t$.

Hence Eq. 12 becomes:

$$m\ddot{z} + c\dot{z} + kz = m\omega^2 X \cos\omega t \tag{13}$$

c.f. $$m\ddot{x} + c\dot{x} + kx = F = F_0 \cos\omega t \tag{14}$$

whose solution is

$$\left|\frac{x}{F}\right| = \frac{1/k}{\sqrt{\left(1-\beta^2\right)^2 + \left(2\zeta\beta\right)^2}} \tag{15}$$

and the phase ϕ is as follow:

$$\tan\phi = \frac{2\zeta\beta}{1-\beta^2} \tag{16}$$

so, by comparison

$$\left|\frac{z}{m\omega^2 x}\right| = \frac{1/k}{\sqrt{\left(1-\beta^2\right)^2 + \left(2\zeta\beta\right)^2}} \tag{17}$$

2.4.1 Accelerometers

It is an instrument with high natural frequency. When the natural frequency of the instrument is high compared to that of the vibrations to be measured, the instrument indicates acceleration. If the transducer measures velocities, the instrument is known as a vibrometer or a velometer. In such cases, the instrument output can be integrated once to obtain displacements, or differentiated once to obtain accelerations.

Due to their small size and high sensitivity accelerometers are preferred in vibration measurements. The acceleration measured can be integrated once or twice with the help of modern electrical circuits to obtain velocity and displacement of the system.

When choosing an accelerometer there are certain aspects to consider. The mass must be as small as possible in comparison with the mass of the structure to be measured. For human measurement, accelerometers weighting only 1-2 grams are desirable. Furthermore, the dynamic amplitude range must be able to accommodate the maximum acceleration level anticipated and the frequency response must match the overall frequency spectrum measured. Accelerometers should only be used for measurement of frequencies specified by the manufacturer. Each measuring device has a usable frequency band where its response is optimised. Below and above this band the device will not be able to correctly puck up the signals and measure them. In the region above the usable frequency there is another problem with the internal resonant frequency of the instrument resulting in an incorrect, too high response at that frequency. Additionally, environmental factors like high temperature can have a negative effect on the measurements.

The most commonly used accelerometers are the compression-type piezoelectric accelerometers. They consist of a mass resting on a piezoelectric ceramic crystal, such as quartz, barium titanate, or lead zirconium titanate, with the crystal acting both as spring and sensor. The accelerometers have a preload providing a compressive stress exceeding the highest dynamic stress expected. Any acceleration increases or decreases the compressive stress in the piezoelectric element, thus generating an electric charge appearing at the accelerometer terminals. Piezoelectric accelerometers have negligible damping and they typically have a frequency range from 0 to 10.000 Hz (and beyond) and a natural frequency range from 30.000 to 50.000 Hz. They tend to be very light, weighting less than 20g, and are relatively small, measuring less than 2 cm in diameter [1].

2.4.2 Seismometers

It is an instrument with low natural frequency. Because seismometers require a much larger mass than accelerometers and the relative motion of the mass in a seismometer is nearly equal in magnitude to the motion to be measured, seismometers are considerably larger in size than accelerometers. Thus, if the interest lies in displacements, it may prove more desirable to use an accelerometer to measure the acceleration of the case, and then integrate twice with respect to time to obtain the displacement.

References – Chapter 2

[1] Meirovitch, L. Fundamentals of Vibrations. McGraw-Hill International Edition, 2001.

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CHAPTER 3

Heat exchange between the human body and the environment

In this chapter, a brief introduction to the heat exchange between the human body and the environment is carried out. Emphasis is given to the human metabolism, the thermoregulation process and its influencing factors

3.1 Human metabolism

Metabolism is the biochemical modification of chemical compounds in living organisms and cells. These processes allow organisms to grow and reproduce, maintain their structures, and respond to their environments. The metabolic pathways form a two-part process: one part is called catabolism, in which a cell breaks down complex molecules to yield the chemical energy and reducing power; and the other is called anabolism in which a cell uses chemical energy and reducing power to construct complex molecules, and perform life functions such as creating cellular structure.

Metabolism involves complex and often-interactive biochemical reactions usually aided by *enzymes* and often coordinated by anabolic and catabolic hormones. Enzymes present in cells can catalyze a large variety of chemical reactions with exquisite specificity. Generally, enzymes are protein molecules that make reactions go faster by bringing the reactant molecules close together in just the right orientation for a chemical change to occur. Sometimes these enzymes are floating free in the cytoplasm of the cell, other times they are correlated together within a compartment of the cell, a special organelle. For example, the mitochondrion of cells contains enzymes for oxidative phosphorylation (a catabolic process). The Golgi apparatus of cells contains many of the enzymes used for protein posttranslational modification (an anabolic process). For purposes of analysis and conceptualization, metabolism is commonly characterized in terms metabolic pathways, which are a specific sequence of enzyme-catalysed steps. The total metabolism includes all biochemical processes of an organism. The cell metabolism includes all chemical processes in a cell. For what concern the hormones, some hormones have anabolic actions on the body, others have mainly catabolic actions. For example, testosterone is an anabolic hormone, and synthetic steroids that produce the anabolic actions are known as anabolic steroids. Cortisol on the other hand, which is a steroid hormone produced by the adrenal gland, is a catabolic hormone.

Metabolism is a unifying aspect of all forms of life, with the most complex forms of life relying on some of the same metabolic pathways found in single-celled organism. Knowledge of metabolism has accumulated over a period of more than 400 years, and especially in the first half of the twentieth century, through the experiments and studies of hundreds of research scientists.

Human cells obtain most of their energy from chemical reactions, involving oxygen. A starting point in measuring human metabolism is with basal metabolic rate. Basal metabolic rate (BMR) is the amount of energy expended while at rest in a neutrally temperate environment, in the post-absorptive state (meaning that the digestive system is inactive, which requires about twelve hours of fasting in humans). The release of energy in this state is sufficient only for the functioning of the vital organs, such as the heart, lungs, brain and the rest of the nervous system, liver, kidneys, sex organs, muscles and skin. BMR decreases with age and with the loss of lean body mass. Increased muscle mass can increase BMR. BMR is measured under very restrictive circumstances when a person is awake, but at complete rest. An accurate BMR measurement requires that the person's sympathetic nervous system not be stimulated. A more common and closely related measurement, used under less strict conditions, is resting metabolic rate (RMR). Basal metabolic rate and resting metabolic rate are measured by gas analysis through either direct or indirect calorimetry, though a rough estimation can be acquired through an equation using age, sex, height, and weight. Studies of energy metabolism using both methods provide convincing evidence for the validity of the respiratory quotient (R.Q.), which measures the inherent composition and utilization of carbohydrates, fats and proteins as they are converted to energy substrate units that can be used by the body as energy.

The metabolic rate is often measured in the unit "*Met*". The metabolic rate of a relaxed seated person is one Met, where: 1 Met = 58,2 W/m^2 = 50 $kcal/hm^2$.

Some values of metabolic rates for various typical activities are presented in Table 1.

Living things, like all things, obey the laws of thermodynamics. That means that energy and matter cannot be created from nothing; cool things always get colder rather than warmer, and each fragment of a whole are smaller than the whole itself. The second law of thermodynamics states that in any closed system, the amount of entropy (disorder) will tend to increase. Although living organisms' amazing complexity appears to contradict this law, life is possible as all organisms are open systems that exchange matter and energy with their surroundings. Thus living systems are not in equilibrium, but instead are dissipative systems that maintain their state of high complexity by causing a larger increase in the entropy of their environments [1]. The metabolism of a cell achieves this by coupling the spontaneous processes of catabolism to the non-spontaneous processes of anabolism. In thermodynamic terms, metabolism maintains order by creating disorder [2].

As the environments of most organisms are constantly changing, the reactions of metabolism must be finely regulated to maintain a constant set of conditions within cells, a condition called

homeostasis [3]. Metabolic regulation also allows organisms to respond to signals and interact actively with their environments [4].
The human body is warm-blooded and it must maintain a body temperature within very close limits. It uses food as a fuel, converting it into energy. Some of this energy may leave the body in the form of external work done; the balance represents heat production within the body and is available for the maintenance of body temperature. As the body must produce heat continuously, it must also lose it at a rate that provides control of body temperature. An understanding of the thermal environment can therefore best be developed by considering how it influences the ability of the human body to maintain a suitable rate of heat loss. Comfort may be regarded both physically and physiologically as a condition of thermal neutrality under which the body need not strain to reduce or increase heat loss.
The equation which describes heat balance is:

$$\dot{M} = \dot{R} \pm \dot{C} \pm \dot{K} - \dot{E} \qquad (1)$$

where:
M = metabolic rate of human body, W/m^2
E = rate of total evaporative loss due to evaporation of sweat, W/m^2
R = heat exchange to and from (±) the environment by radiation (R), W/m^2.
C = heat exchange to and from (±) the environment by convection, W/m^2.
K = heat exchange to and from (±) the environment by conduction, W/m^2.

The equation indicates that the internal heat production must be in balance with the four ways in which it may be disposed. Some heat may be stored, or drawn from storage within the body, with a corresponding change in body temperature over short periods. Most of the heat, however, must be rejected from the body surfaces through convection losses to the surrounding air, by radiation exchanges with surrounding surfaces, and by the evaporation of perspiration from the skin when required. Although not listed specifically, there will be a loss of heat through the heat and water vapour added to the air involved in respiration.
Heat production is determined by metabolic activity. When at rest, this is the amount needed for the body's basic functions, as e.g. respiration and heart function to provide body cells with oxygen and nutrients. When working however, the need of the active muscles for oxygen and nutrients increases, and the metabolic activity increases. When the muscles burn these nutrients for mechanical activity, part of the energy they contain is liberated outside the body as external work, but most of it is released in the muscle as heat. The ratio between this external work and

the energy consumed is called the efficiency with which the body performs the work. This process is similar to what happens in a car engine. The minor part of the fuel's energy is actually effective in the car's propulsion, and the mayor part is liberated as waste heat. The body, as the car engine, needs to get rid of this heat; otherwise it will warm up to lethal levels. As an example: if no cooling would be present, a person working at moderate levels (metabolic rate 450 Watt) would show an increase in body temperature around 1°C every 10 minutes.

During the kinetic evolution of the performance, a correction factor is introduced and Eq. 1 becomes:

$$\dot{S} = \dot{M} \pm \dot{R} \pm \dot{C} \pm \dot{K} - \dot{E} \qquad (2)$$

where the term $\dot{S}$ corresponds to the so-called "body heat storage" [12] and it can also be called as "thermal inertia" of the human body. The "thermal inertia" quantifies the body trouble (inertia) to change its thermal status.

The following equation is used for the estimation of the "thermal inertia" $\dot{S}$:

$$\dot{S} = \left(C_b g \Delta T_b\right) / dt \qquad (3)$$

where:

g = body weight

C_b = specific heat of the body, assumed to be 3.47 kJ/kg ºK [25]

ΔT_b = mean body temperature determined by a weighted average of ΔT_{sk} (skin) and ΔT_{re} (rectal) as proposed by Burton [13] $\left(0.65\Delta T_{re} + 0.35\Delta T_{sk}\right)$ or by Stolwijk and Harly [23] $\left(0.8\Delta T_{re} + 0.2\Delta T_{sk}\right)$.

It is also clear that during exercise (in hot environment) the thermal inertia of the body cannot be determined from any fixed ratio of both inner and skin temperature [24].

The metabolic rate of human body $\dot{M}$ can be estimated by measuring the fuel uptake (oxygen) and quantitatively using the following equation:

$$\dot{M} = 352\left(0.23r + 0.77\right)VO_2 \qquad (4)$$

where:

r = respiratory factor

VO_2 = volume of oxygen uptake

Table 1 Metabolic Rates.

Activity	W/m^2	Met
Reclining	46	0.8
Seated relaxed	58	1.0
Standing relaxed	70	1.2
Sedentary activity (office, dwelling, school, laboratory)	70	1.2
Car driving	80	1.4
Graphic profession – Book Binder	85	1.5
Standing, light activity (shopping, laboratory, light industry)	93	1.6
Teacher	95	1.6
Domestic work – shaving, washing and dressing	100	1.7
Walking on the level, 2 km/h	110	1.9
Standing, medium activity (shop assistant, domestic work)	116	2.0
Building industry – Brick laying (Block of 15.3 kg)	125	2.2
Washing dishes standing	145	2.5
Domestic work – raking leaves on the lawn	170	2.9
Domestic work – washing by hand and ironing (120-220 W)	170	2.9
Iron and steel – ramming the mould with a pneumatic hammer	175	3.0
Building industry – forming the mould	180	3.1
Walking on the level, 5 km/h	200	3.4
Forestry – cutting across the grain with a one-man power saw	205	3.5
Volleyball	232	4.0
Calisthenics	261	4.5
Building industry – loading a wheelbarrow with stones and mortar	275	4.7
Bicycling, Golf, Softball	290	5.0
Gymnastics	319	5.5
Aerobic Dancing, Basketball, Swimming	348	6.0
Sports – Ice skating, 18 km/h	360	6.2
Agriculture – digging with a spade (24 lifts/min.)	380	6.5
Skiing on level, good snow (9 km/h), Skating ice, Tennis	405	7.0
Forestry – working with an axe (weight 2 kg. 33 blows/min.)	500	8.5
Sports – Running in 15 km/h	550	9.5

3.2 Thermoregulation in the human body

In a neutral climate, at rest, the human body regulates its core temperature around 37°C. This is by no means an exactly fixed temperature for all humans. It is the role of the thermoregulatory system to vary the level of heat exchange with the environment so as to maintain deep body temperature within about half a degree Celsius of the normal deep body temperature of 37°C. When measuring in the morning after bed-rest, the mean will be around 36.7°C, with a standard deviation of 0.35°C [5]. During the day, the temperature will increase (typically by ±0.8°C), peaking in the late evening, and declining again until early morning due to the circadian rhythm. In addition, exercise increase the body temperature, with temperatures around 38°C for moderate work and values up to 39°C for heavy work (e.g. marathon).

In order to control body temperature the thermoregulatory system must be able to sense temperature and respond to changes. Thus, it includes the so-called thermoreceptors that respond to increases (warm receptors) and decreases (cold receptors) in temperature. These receptors can be found in areas of the body such as the skin, muscles, spinal cord, and brain. In the skin for example, there are about three times more cold than warm receptors. They are located about 0.18 mm below the surface of the skin; this means that they respond quickly to changes in environmental temperature. At constant temperatures (within an appropriate range), cold receptors are continuously active electrically, the frequency of the steady discharge (static response) depending on temperature. In most cases the static activity reaches a maximum at temperatures between 20° and 30°C. On sudden cooling to a lower temperature level, the cold receptors respond with a transient increase in frequency (dynamic response); if the lower temperature is maintained, the frequency drops to a level of static discharge in adaptation. When the receptor is warmed up again, a transient decrease in electrical activity is seen, after which the frequency rises again and finally adapts to the initial static value. Warm receptors are also continuously active at constant temperatures, with a maximum at 41° to 46°C. On sudden temperature changes, warm receptors respond in the opposite direction from that of cold receptors, temporarily overshooting adaptation frequency on warming and showing transient inhibition on cooling. Thermoreceptors are thus selectively sensitive to specific ranges of temperature as well as to rate of temperature change. In the area of the brain that is particularly sensitive to temperature, called the hypothalamus, there are more warm than cold receptors. These are not stimulated until changes in environmental temperature, or metabolic heat production (e.g. exercise), have an impact on the temperature of the brain via the blood flowing through it.

In human beings, the function of thermosensors is closely involved in the highly emotional experiences of thermal comfort and discomfort. Whereas temperature sensations are mainly related to the activity of warm and cold receptors in the human skin, thermal comfort and discomfort reflect the general state of the thermoregulatory system, involving signals not only from thermoreceptors in the skin but from thermoreceptors in deep-body regions and in the hypothalamus as well. Thus, the same temperature at the skin can be experienced as comfortable or uncomfortable, depending on the thermal condition of the person's whole body. When one is overheated, an ice bag applied to the head may be perceived as pleasant; but, if someone is generally chilled just to the point of shivering, the same cold stimulus can be most unpleasant.

The thermoregulatory responses evoked are the result of an integration of the inputs from peripheral and central receptors. This integration take place in the hypothalamus. Hence, the hypothalamus is not only sensitive to its own temperature, it also receives and processes thermal information from the remainder of the body and initiates appropriate responses. The hypothalamic thermoregulatory centre contains neurons with specific temperature sensitivity. Not only the preoptic anterior area contain thermosensitive neurons, but also ventromedial and posterior hypothalamus. Thermosensitive neurons have also been found along the internal carotid artery, the medulla oblongata and skeletal muscle. They respond to changes in the blood temperature. The extra-hypothalamic thermosensitive neurons are able to sense and modulate thermal signals. The temperature receptors in the brain are more important in determining the type and magnitude of thermoregulatory responses than those in the periphery. This relationship has practical consequences and, for example, explains why hand cooling can be used to cool a hyperthermic individual, but not to re-warm a hypothermic one.

3.2.1 Factors influencing thermoregulation

This paragraph describes the factors that influence the thermoregulation of the human body. In particular: the climate, the acclimatization, the exercise, the clothing, the age and the body posture and its changes.

3.2.1.1 Climate

- **Response of the human body to cold**

The body core temperature is regulated within a narrow range around 37°C in order to maintain optimal physiological function. For a nude resting individual, the ideal ambient temperature is about 28 to 30°C. Under such conditions the mean skin temperature is about 33°C, and the body core temperature is about 37°C. If the ambient temperature drops, the temperature difference between the skin and the environment is increased; this causes an increased heat loss through convection and radiation and a drop of the mean skin temperature [6]. A reduced heat flow to the skin would result in a gradual lowering of the skin temperature. This would produce a reduced temperature gradient between the ski and the environment.

The major physiological protective mechanisms in cold are peripheral vasoconstriction and cold-induced thermogenesis by shivering.

When the temperature of the environment is cold, there is a reduction of the blood flow to the skin and the underlying fatty layer. In so doing, it converts both into an insulating buffer zone on the surface of the body that protects the inner "core" temperature where the vital organs are situated. Insulation is defined as resistance to heat flow, and the thicker the layer of fat beneath the skin, subcutaneous fat, the better the resulting insulation in the cold. Thus, reducing skin blood flow is the means by which peripheral insulation is employed. The fat beneath the skin can be regarded as "fixed" insulation that changes little in the medium term. Muscle can also provide significant levels of insulation when it is relatively unperfused by blood, i.e. at rest. However, this source of insulation is lost at relatively low levels of exercise; this includes shivering. The reduction in skin blood flow decreases the amount of heat delivered to the surface of the body. As a consequence skin temperature is lowered and becomes closer to the temperature of the environment; this reduces the gradient down which heat can be lost to that environment.

In addition, an increase of the metabolic rate is a protective mechanism to maintain heat balance through muscle activity in the form of shivering by a reflex mechanism. Shivering is the involuntary, synchronous and rhythmic contraction of small parts of skeletal muscles and is an involuntary response to reduced temperature of the preoptic area in the hypothalamus and/or peripherical temperature. This defence mechanism is activated only when behavioural compensations and maximal arterio-venous shunt vasoconstriction are insufficient to maintain core temperature. The benefit of shivering is an increased heat production, up 5-6 times above basal level, which may prevent further cooling. Alpha motorneurons are activated and coordinated in an oscillatory mode. Finally, if the thermoregulatory defence mechanisms are insufficient to maintain the body temperature steady above 35°C, hypothermia develops.

The energy required for shivering comes from fats and sugar. Of the two, it is sugar (carbohydrate) that is in the shortest supply and, when it runs out, shivering stops. Even with moderate levels of shivering this can occur in as little as 7 hours when no food is eaten. Shivering is also reduced when oxygen levels in the inspired air fall, or carbon dioxide levels increase; this becomes important in situations where ventilation can be inadequate, such as in life rafts. Shivering uses the same skeletal muscles as voluntary exercise and the two can co-exist up to moderate levels of voluntary activity. With mild cooling, shivering is progressively inhibited as exercise intensity increases. With severe cooling the increase in muscle tone associated with shivering can inhibit co-ordinated movement and impair activities such as swimming.

Cold stress is recognised in many ways. First a feeling of cold appears, then manual dexterity is reduced and may be lost, behaviour becomes unsafe, accidents may happen as a partial result of cooling and shivering may occur [8].

Cold also affects locomotion. At low temperatures nerve and motor function are impaired. Cooling slows the signal conduction in the nerves. Cold joints become stiff, which increases the resistance to movements. Muscle power, force and endurance are decreased by cold. Slow cooling has been shown to have larger effect on performance than rapid cooling, probably because the temperature of deeper tissues becomes lower [7].

Increased blood pressure is also connected to cold exposure. One very important function of the blood circulation is to transport heat: to cool or to heat various tissues as may be needed, and to carry excess body heat from the interior of the body to the body surface; i.e. skin. The blood is very effective in this function, for it has a high heat capacity, which means that the blood may carry a great deal of heat with only a moderate increase in temperature. In cold conditions, the total peripheral resistance is increased due to the skin vasoconstriction and at rest about 20% of the cardiac output is redistributed from the skin to more central part of the body. Total peripheral resistance may account for a great part of the pressure rise. In normal temperature baroreceptor reflexes are elicited in response to the increased venous return and bradycardia follows. The reflex bradycardia is of parasympathetic origin.

In addition to the mentioned effects of cold, the water balance is affected. With a cold-induced increase of systolic blood pressure, the renal artery perfusion pressure increases. A secondary rise in capillary pressure increases the hydrostatic gradient and results in a reduced sodium resorption. Sodium losses in the urine are accompanied by fluid losses [9].

Hypothermia

Hypothermia is a condition usually characterized by body temperatures below 35°C. When the body is exposed to cold its internal mechanisms may be unable to replenish the heat that is being lost to the organism's surroundings.

Hypothermia is divided into two types: primary and secondary. Primary hypothermia occurs when the body's heat-balancing mechanisms are working properly but are subjected to extreme cold, whereas secondary hypothermia affects people whose heat-balancing mechanisms are impaired in some way and cannot respond adequately to moderate or perhaps even mild cold. Primary hypothermia typically involves exposure to cold air or immersion in cold water. The cold air variety usually takes at least several hours to develop, but immersion hypothermia will occur within about an hour of entering the water, since water draws heat away from the body much faster than air does. In secondary hypothermia, the body's heat-balancing mechanisms can fail for any number of reasons, including strokes, diabetes, malnutrition, bacterial infection, thyroid disease, spinal cord injuries (which prevent the brain from receiving crucial temperature-related information from other parts of the body), and the use of medications and other substances that affect the brain or spinal cord. Alcohol is one such substance. In smaller amounts it can put people at risk by interfering with their ability to recognize and avoid cold-weather dangers. In larger amounts it shuts down the body's heat-balancing mechanisms.

The signs and symptoms of hypothermia follow a typical course. Though the body temperature at which they occur vary from person to person depending on age, health, and other factors. Some of the first signs of hypothermia may be lack of coordination, cold and pale skin, and intense shivering. As body temperature begins to fall, speech becomes slurred, muscles go rigid, vision problems develop, and the patient becomes disoriented. At body temperatures below 32°C, heart rate, respiratory rate, and blood pressure fall. Eventually the patient loses consciousness and may appear to be dead. At even very low temperatures, however, a person may survive for several hours. They can sometimes be successfully revived.

· **Response of the human body to heat**

When the human body is exposed to heat, or during muscle activity, the heat content of the body tends to increase. Under such conditions, the blood vessels of the skin dilate, venous return in the extremities takes place through superficial veins, and the conductance of the tissue increase. The increased heat flow to the skin increases the skin temperature. If the temperature of the surroundings is lower than that of the skin, heat loss is facilitated through convection and radiation. If the heat load is sufficiently large, the sweat glands are activated, and as the produced sweat is evaporated, the skin is cooled.

There are two types of sweat glands, eccrine sweat glands and apocrine sweat glands (Fig. 1). Both types of glands are controlled by the sympathetic nervous system.

There are between 2 and 4 million sweat glands found across the human body.

When it comes to regulating body temperature eccrine sweat glands play a major role. These sweat glands are found all over the body but particularly concentrated on the palms soles and forehead. These areas consequently produce sweat composed chiefly of water along with small amounts of various salts. So in effect eccrine glands are used for body temperature regulation. Eccrine sweat glands are present mainly in the outer layer of the human skin but also extend into the inner layer. The glands are under controlled by sympathetic cholinergic nerves which are in turn controlled by the hypothalamus. So it is the hypothalamus that senses a change in temperature both directly as well as from messages it receives from temperature receptors in the skin. Once it realizes the need for temperature regulation it modifies the sweat output.

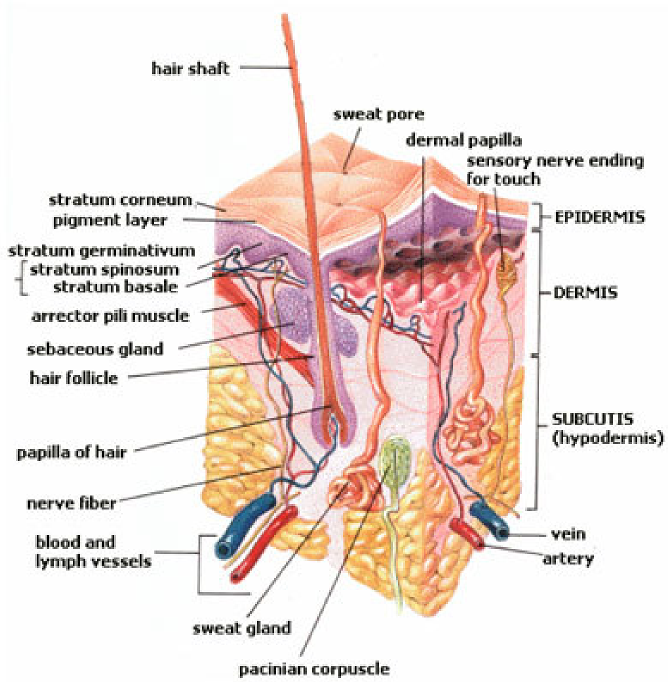

Figure 1 Human skin and sweat glands.

Apocrine glands make their presence felt in the human body during early to mid-puberty which means approximately around the ages of 12-15. Initially they release more than the normal amount of sweat and then settle down to regulate and release normal amounts of sweat after a certain period. Unlike eccrine glands the sweat from apocrine sweat glands contains fatty materials. Also unlike eccrine glands apocrine glands are concentrated in the underarms and around the genitals. It is with these glands that body odor is associated because apocrine sweat attracts bacteria that break down the organic compounds present in it and release the odor. Thus apocrine glands basically serve as scent glands. While eccrine glands secrete more amounts of sweat during heightened physical activity or an increase in external temperature it is emotional stress that accelerates the production of sweat from apocrine glands.

The individual difference in the capacity for sweating is considerable; some people have no sweat glands at all. As a person becomes accustomed to heat, the amount of sweat produced in response to a standard heat stress increases. A person may produce several liters of sweat per hour. Workers exposed to intense heat may lose as much as 6 to 7 liters of sweat in the course of the working day.

During prolonged exposure to a hot environment, there is a gradual reduction in the sweat rate, even if the body water loss is replaced at the same rate. This decline in sweat rate is greater in humid than in dry heat [6].

Sweat contains mainly water. It also contains minerals, as well as lactate and urea. Mineral composition will vary with the individual, the acclimatization to heat, exercise and sweating, the particular stress source (exercise, sauna, etc.), the duration of sweating, and the composition of minerals in the body.

Exposure of resting subjects to direct whole-body heating causes a rise in skin temperature that is accompanied by an almost immediate rise in heart rate and cardiac output, and a drop in total peripheral resistance and splanchnic blood flow.

Furthermore, the magnitude of air movement effects both convective and evaporative heat losses. For both avenues, heat exchange increases with increasing wind speed. Thus in a cool environment the body cools faster in the presence of wind, in an extremely hot, humid environment, it will heat up faster.

Hyperthermia

Hyperthermia is an acute condition which occurs when the body produces or absorbs more heat than it can dissipate and it is usually caused by prolonged exposure to high temperatures. The most serious consequence of exposure to intense heat is heat stroke, which can be fatal. It is caused by a sudden collapse of temperature regulation leading to a marked rise in body heat content. The rectal temperature may be 41°C or higher. The skin is hot and dry. There are tachycardia and hypotension, metabolic acidosis, disseminated intravascular coagulation, and occasionally renal failure. The victim is confused or unconscious. This form of temperature-regulatory failure is rare. The risk is higher in nonacclimatized than in acclimatized individuals. Obese persons and older individuals are most susceptible [6].

Since heat stroke often is associated with peripheral circulatory collapse, the oral temperature of the victim may not necessary be very high, while the rectal temperature always is. Another type of temperature-regulation failure is the so-called anhidrotic heat exhaustion. The victim may have a body temperature of 38°C to 40°C, and may sweat very little or not at all. The main trouble is reduced sweat production. When the patient stop exercising and is removed to a cool place, this condition rapidly improves. A third type of serious disturbance due to heat exposure is excessive loss of fluid and salt, usually because of failure to replace fluid and salts lost through sweating.

Brain function is particularly vulnerable to heat [10]. Tolerance to elevated deep body temperature is extended, if the brain is kept cool [11]. According to Baker [10], studies in human show that changes in heat loss from the face have a powerful effect on thermoregulation, which may be caused by a change in hypothalamic temperature.

3.2.1.2 Acclimatization

Acclimatization is the process of physiological and behavioral adjustments of an organism to changes in its environment (continuous or repeated exposure to heat, and possibly also to cold).

· **Heat acclimatization**

Heat acclimatization refers to biological adaptations that reduce physiologic strain (e.g., heart rate and body temperature), improve physical work capabilities, improve comfort and protects vital organs (brain, liver, kidneys, muscles) from heat injury. The most important biological adaptation from heat acclimatization is associated with increased sweat production, a lowered skin and body temperature, and a reduced heart rate [6]. After a few days exposure to a hot environment, the individual is able to tolerate the heat much better that when first exposed.

Complete heat acclimatization requires up to 14 days, but the systems of the body adapt to heat exposure at varying rates. The first phase of acclimatization (initial 1-5 days) involve an improved control of cardiovascular function, including expanded plasma volume, reduced heart rate, and autonomic nervous system habituation which redirects cardiac output to skin capillary beds and active muscle. Plasma volume expansion resulting from increased plasma proteins and increased sodium chloride retention, ranges from +3 to +27%, and is accompanied by a 15-25% decrease in heart rate. This reduction of cardiovascular strain reduces rating of perceived exertion, which is proportional to central cardiorespiratory stress, also decreases during the first five days of exercise-heat exposure. Plasma volume expansion is a temporary phenomenon, which decays during the 8th to 14th days of heat acclimatization (as do fluid-regulatory hormone responses, see below), and then is replaced by a longer-lasting reduction in skin blood flow that serves to increase central blood volume.

The regulation of body temperature during exercise in the heat is critical, because of the great potential for lethal hyperthermia. Thermoregulatory adaptations (i.e., increased sweat rate, earlier onset of sweat production), coupled with cardiovascular adjustments, result in a decreased central body temperature. This response is maximized after 5 to 8 days of heat acclimatization. However, the adaptations of eccrine sweat glands are different during humid and dry heat exposures. Heat acclimatization performed in a hot-humid condition stimulates a greater sweat rate than heat acclimatization in a hot-dry environment. Also, the absolute rate of sweating influences thermoregulation. If hourly sweat rate is small (<400-600 ml), a peripheral adaptation of whole body sweat rate may not occur [20].

Finally, seasonal differences in acclimatization to heat have been reported in human [19]. Acclimatized humans in winter season exhibited lower sweat rates than in summer. During winter acclimatization, the blood volume expansion was due to the expansion both in the plasma and cellular compartments, whereas in the summer the acclimatization resulted in only plasma volume expansion.

· **Cold Acclimatization**

Cold acclimatization is the process of physiological adaptations to repeated, prolonged exposure to low temperatures. Thermal adaptation, either natural acclimatization or artificially produced acclimation, to cold takes ca. two weeks. After the development of adaptation, the physiological responses to cold are usually attenuated and cold environment is subjectively considered less stressful than before adaptation.

Cold adaptation of hands diminishes the local vasoconstriction which allows higher circulation and skin temperatures in hands (fisherman's hands). The classical forms of physiological cold acclimatization are insulative (increased skin vasoconstriction or subcutaneous fat), hypothermic (decreased core temperature), insulative-hypothermic (most common type of cold acclimatization) and metabolic (increased energy consumption). Behavioral adaptation is most important for the survival of human species. It includes e.g., well heated houses, good thermal insulation of clothing, warm vehicles and short exposures to cold. In fact, behavioral adaptation can work so well, that no physiological adaptation is developed in winter [22].

According to some studies [6], the metabolic rate of individuals exposed in cold is often elevated when they are exposed nude to a standardized cold stress, even though shivering is said to be less pronounced. It is possible that hormones, notably norepinephrine, play a role in the elevation of the metabolic rate, but the mechanism is unclear.

LeBlanc [21] found that repeated exposure of the hands and face to severe cold activates some adaptive mechanisms characterized by a diminution of the sympathetic response and a concomitant enhancement of the vagal activation normally observed when the extremities and the face are exposed to cold.

However, any physiological adaptation to cold in humans is of little practical value compared with the importance of know-how, experience, and state of physical fitness. There is definitely a limited capacity of the automatic thermostatic system. The success of the Eskimo in getting along in the cold depends on their ability to avoid the extreme cold. Since most arctic clothing (except fur clothing) is inadequate in terms of insulation to maintain thermal balance when an individual is exposed without shelter to extreme prolonged cold, the only way to survive is to remain active in order to increase the heat production. The fitter the Eskimo are, the longer they can do this. Thus, survival in Arctic is a matter of survival of the fittest.

3.2.1.3 Exercise

Since the mechanical efficiency of the human body is mostly below 25%, more than 75% of the total energy utilized is converted into heat. The greater the exercise intensity, the greater the total amount of heat produced. This excess heat has to be removed and dissipated in order to prevent overheating and hyperthermia.

During prolonged light exercise in a hot environment, the heart rate rises markedly while cardiac output increases more gradually for 30 to 40 min in spite of a progressive fall in stroke volume. During prolonged moderate to heavy exercise, the heart rate does not reflect changes in cardiac output or in skin blood flow. Actually, stroke volume decreases while cardiac output is maintained by increased heart rate.

The control of peripheral circulation in dynamic exercise in the heat may be complicated by changes in body position and especially by the upright position [14 - 16].

During submaximal exercise in a hot environment there is evidently a different blood flow distribution as compared with exposure to a normal climate. At a given cardiac output, more blood flows through the skin and less through the active muscle mass. This might explain the higher blood lactate concentration observed in the warm environment.

As a conclusion we can say that muscular exercise may increase the heat production from 10 to 20 times the heat production at rest. During exercise in a "neutral" environment, there is an increase in body temperature up to a maximum of about 40°C or slightly higher at maximal work rates. The body temperature is not related to the absolute heat production but to the relative work rate, i.e., actual oxygen uptake in relation to the individual's maximal aerobic power; at a 50% load, the deep body temperature is about 38°C. The deep body temperature at rest and during exercise is, within a wide range, not affected by the environmental temperature; but the skin temperature is. In a given environment, the sweating rate is mainly dependent on the actual heat production and not primarily on the skin or rectal temperature.

3.2.1.4 Clothing

Human thermal comfort depends on combinations of clothing, climate, and physical activity. Particularly thermal insulation in clothing is an important parameter of thermal comfort. Therefore, clothing is needed to protect the body against climatic influence and to assist its own thermal control functions under various combinations of environmental conditions and physical activities. The heat loss from the body and the feeling of individual comfort in a given environment is much affected by the clothing worn.

Clothing acts as a barrier for heat and for vapour transport between the skin and the environment. This barrier is formed both by the clothing materials themselves and by the air they enclose and the still air that is bound to its outer surfaces.

Dry heat transfer through clothing materials consists mainly of conduction and radiation. For most clothing materials, the volume of air enclosed is far greater than the volume of the fibres. Therefore the insulation is very much dependent on the thickness of the material (i.e. the enclosed air layer) and less on the fibre type. The fibres mainly influence the amount of radiative heat transfer, as they reflect, absorb and re-emit radiation. That this effect is of minor importance relative to the thickness (except for special reflective clothing) can be seen in Fig. 2, where the insulation of a range of different clothing materials is presented in relation to their thickness.

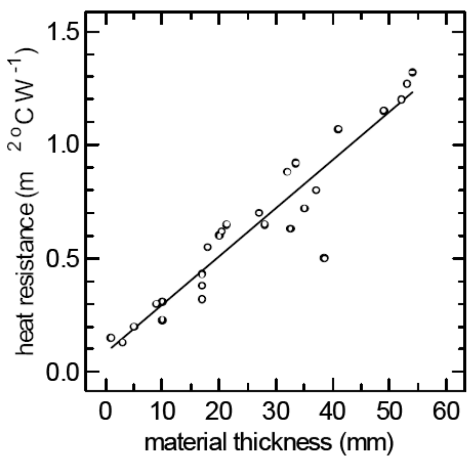

Figure 2 Relation between clothing material insulation and the material thickness [17].

Thickness appears to be the major determinant of insulation [18]. For normal, permeable materials, clothing material thickness also determines the major part of the clothing vapour resistance. Again, as the volume of fibres is usually low compared to the enclosed air volume, the resistance to the diffusion of water vapour through the garments is mainly determined by the thickness of the enclosed still air layer. With thin materials, the fibre component gets a more important role as there e.g. different weave characteristics affect the diffusion properties more than in thick materials.

The insulation of clothes are often measured with the unit "Clo", where: 1 Clo = 0.155 m2K/W. Clo = 0 corresponds to a naked person and Clo = 1 corresponds to a person wearing a typical business suit (see Table 2).

In order to remain in heat balance, a person sleeping outdoors at -40°C needs protective clothing with an insulation value about 12 Clo units. However, when the same individual is physically active, moving about or walking along, only the equivalent of 4 Clo units will be needed because the person's body heat production is now at least 3 times greater than it was when sleeping because of the increased metabolic rate associated with the increased physical activity.

The insulation value of most materials is proportional to the amount of air that is trapped within the material itself, since air is such a superb insulator. In the case of fur, air is trapped in the space between each hair, but the superior insulation quality of caribou fur, over and above other fur, lies in the fact that the caribou hair is hollow and contains trapped air inside each hair as well as in the spaces between them. As a rough estimate, the insulating value of most clothing is approximately 1,6 Clo cm^{-1}. As the insulating value is primarily a function of the amount of trapped air in the clothing, the type of fibre used is of less important.

Table 2 The insulation of clothes.

Clothing	Clo	m^2K/W
Pantyhose	0.02	0.003
Panties	0.03	0.005
Bra	0.01	0.002
Shirt sleeveless	0.06	0.009
T-shirts	0.09	0.014
Shirt with long sleeves	0.12	0.019
Short sleeve	0.09	0.029
Light shirt with long sleeves	0.20	0.031
Shorts	0.06	0.009
Light summer jacket	0.25	0.039
Jacket	0.35	0.054
Socks	0.02	0.003
Thin soled shoes	0.02	0.003
Boots	0.05	0.008
Light dress sleeveless	0.25	0.039
Heavy skirt knee-length	0.25	0.039
Under shorts	0.10	0.016
Long sleeve, wrap, short	0.41	0.064
Long sleeve, wrap, long	0.53	0.082

3.2.1.5 Age

At different ages, the human body varies and changes so its thermoregulation and its response to cold and hot environments.

The aging process results in a more lethargic response of the sweat glands, which leads to a less effective control of body temperature.

Older people are at high risk for developing heat-related illness because the ability to respond to heat can become less efficient with advancing years. Age-related changes may include changes to the skin, such as poor blood circulation and inefficient sweat glands. The body's ability to conserve water is reduced; the sense of thirst becomes less acute, and the body is less able to respond to changes in temperature. Because of these changes, older adults may not sense the change in temperature and respond appropriately. Chronic illness, hormonal changes associated with menopause, use of certain medications, disability, and outright neglect are also issues that affect many older adults and can be contributors to heat illness.

Children produce more heat than adults and they also sweat less. Finally, for women, it has been found that the skin temperature increases with age in moderate and high heat loads, but not in low heat loads.

3.2.1.6 Body posture and its changes

In order to determine the extent of cooling processes the concerned body's surface size is of fundamental importance. The size of the geometrical surface of a human being (*S*) can be calculated with the following empirical formula (Dubois):

$$S = g^{0.425} \cdot l^{0.725} \cdot 71.84 cm^2 \quad (5)$$

where *g* is the weight and *l* the length of the body.

In a standing nude human, about 80% participates in radiative emission, also in losses through conduction and convection.

References – Chapter 3

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CHAPTER 4

Heat transfer mechanisms of the human body

Heat, generated by metabolic processes, is lost to the environment through four mechanisms: radiation, conduction, convection and evaporation. Convection is dependent on the temperature gradient between the body and the ambient air and is increased by wind. Radiation is dependent on the gradient between the body surface and the environment radiation temperature (temperatures and emissivity of the surfaces). Thus convection and radiation are the main avenue for heat loss in the cold. In actual conditions, the degree of conduction can be neglected. While radiation is easily estimated, convection requires more effort and some assumptions.

In addition to convective cooling, the hands and feet may be cooled by conduction of heat between the body and materials in contact. This may lead to a rapid local heat loss for example at handling of cold materials and standing on cold ground. In normal situations evaporative heat loss constitutes a small part of the total heat loss, but during heavy work, sweating may increase evaporation.

4.1 Conduction

Conduction is the process of heat transfer by random atomic or molecular motion. It can be viewed as the energy diffusion from the region of high temperature to the region of low temperature through a body or across an interface between two bodies. Thermal energy is transferred by the form of kinetic energy due to vibration and collision of molecules. Higher vibrating molecules of a warmer object will collide with slower vibrating molecules of a colder object, resulting in a net transfer of energy from the higher vibrating molecules to the slower ones. The rate of heat transfer by conduction is proportional to the area through which heat is flowing and the temperature gradient (steeper gradient higher rate, for the same area), and depends on the thermal conductivity of the material. Thermal conductivity refers to the ability of material to conduct heat. Solids are, in general, better conductors than liquids and liquids are better conductors than gases. Metals are very good conductors of heat, while air and blubber (fat) are very poor conductors of heat.

The human body is always in contact with some other material substance. When standing it has feet in contact with the floor, when sitting it is in contact with the chair, and when sleeping, in contact with the bed. If a temperature difference exists, there will be a heat transfer. Occasionally, an individual comes in contact with something in a room, which is so different in temperature that it is uncomfortable (such as a hot teapot) and a natural reaction soon rectifies the problem. Any object that is much hotter or much colder than the individual contributes to discomfort. The temperature of objects in the room not only affects conduction, also affect radiation. Thus, we have two reasons for controlling the temperature of the solid objects in the room. Solid objects with large surface areas will be the more important, such as walls, ceilings, floors and windows. The basic heat transfer equation for conduction is:

$$\frac{Q}{t} = \frac{kA\left(T_{hot} - T_{cold}\right)}{d} \qquad (1)$$

where (in the case of human body):

A = area of the human body

k = *thermal conductivity* of the air surrounding the body [J/s-m-C].

In Table 1, some examples of thermal conductivity are displayed:

Table 1 Table of thermal conductivities.

Substance	**Thermal conductivity k[J/(s-m-C)]**	**Substance**	**Thermal conductivity k[J/(s-m-C)]**
Syrofoam	0.010	Glass	0.80
Air	0.026	Concrete	1.1
Wool	0.040	Iron	79
Wood	0.15	Aluminum	240
Body fat	0.20	Silver	420
Water	0.60	Diamond	2450

4.2 Convection

The convective heat transfer process combines the previous conductive mode with the mode of energy transferred by the movement of the fluid. In fluids, convective heat transfer takes place through molecular diffusion (Brownian motion of molecules) and advection, the large scale motion, or flow, due to changes in density (and hence buoyancy) as a fluid warms up or cools down.

As an individual resides in a room, air is in contact (conduction) with the individual, and heat is passed by conduction from the person to the ambient air. The air soaks up this heat and as a result of becoming heated begins to rise upwards. Heated air becomes less dense and thus lighter, causing its rise. This is a convection current. Every person creates a constant convection current as air around that individual is heated.

The basic relationship for heat transfer by convection has the following form:

$$Q = hA\Delta T \quad (2)$$

where:

Q = heat transferred per unit time (W)

h = convective heat transfer coefficient (W/m^{2}K or W/m^2 ^{o}C)

A = heat transfer area of the surface (m^o)

ΔT = temperature difference (K or ^{o}C)

There are two types of convection: natural and forced. Forced convection occurs when a pump or other mechanism moves the heated fluid. Examples of forced-convection apparatuses include some types of ovens and even refrigerators or air conditioners. On the other hand, natural convection occurs when heating itself cause the fluid motion (via expansion and buoyancy force), while at the same time also causing heat to be transported by this motion of the fluid. Both forced and natural types of heat convection may occur together.

The convective heat transfer coefficient h is dependent on the type of media, gas or liquid, the flow properties such as velocity, viscosity and other flow and temperature dependent properties. In general the convective heat transfer coefficient for some common fluids is within the ranges: Air: 10 - 100 (W/m^{2}K) and Water: 500 - 10,000 (W/m^{2}K).

The natural convection boundary layer which forms part of the human micro-environment permits the body to exchange heat with the environment by free convection. This boundary layer has been visualized and measurements of the velocity and temperature profiles within the flow have been described in detail elsewhere [5, 6].

A fluid flowing over the surface of any object forms a thin velocity boundary layer in which viscous effect is more important that the flow outside of this layer. Besides the formation of the velocity boundary layer, with the temperature difference between the surface and the flow, there will be a thermal boundary layer formed on the surface as long as the temperature at the surface is higher that that in the flow. The thickness of the thermal boundary layer may not be the same value as that of the velocity boundary layer.

The convective heat transfer coefficient h is associated to the temperature gradient in the thermal boundary layer. While the thermal boundary layer alters its distribution for different temperature fields, so will the temperature boundary condition between the solid and the fluid interfaces.

When the body is moving through the air, the natural convective boundary-layer flow is displaced and the body loses heat by forced convection. The variables that influence forced convection are the mean air velocity and the nature of the flow (i.e. whether it is laminar or turbulent), and the flow direction. The degree of turbulence and its scale can have a profound effect upon the heat loss.

Many studies of heat loss in forced convection have been carried out and the results were generally expressed in terms of the relationship between the heat transfer coefficient, h_c, and the mean air velocity in which the subject was exposed. Table 2 displays the local convective heat transfer coefficient (h_c), in $Wm^{-2}\ K^{-1}$, during rest and exercises in normal air movement (0.15 – $0.2ms^{-1}$) [7].

Though, a great number of measurements have been made with unidirectional airflows. Kerslake [9] reviews the results of such experiments, and gives the expression $h_c = 8.3\sqrt{v}$, where v is the air velocity in ms^{-1}.

Table 2 Local convective heat transfer coefficient (h_c).

Body region		Head	Chest	Back	Uper arms	Fore arms	Hands	Thighs	Legs	Mean (h_c)
Resting	Sitting	3.2	2.5	2.4	4.0	3.9	4.6	2.8	3.7	3.1
Treadmill exercise	$0.9\ ms^{-1}$	4.2	3.6	3.2	6.4	6.6	7.2	5.0	10.5	5.8
	$1.8\ ms^{-1}$	5.4	4.5	4.3	8.3	10.8	15.4	7.7	14.4	8.4
Free walking	$0.9\ ms^{-1}$	7.2	4.8	4.7	6.0	11.2	11.6	8.7	11.8	8.4
	$1.8\ ms^{-1}$	9.5	6.7	6.7	17.0	16.3	17.2	12.5	17.0	12.0
Bicycle	60 rpm	4.4	3.3	3.2	5.3	5.2	4.7	6.7	11.1	6.0

Measurements of the heat loss distribution around the human head revealed the dependence of forced convection on air flow direction in a unidirectional air stream [18]. In reality, the body is rarely subjected to truly linear forced convective flows. During walking and running, the trunk and the head of the human body performs a motion similar to a straight line translation through the air. The moving limbs perform swinging motion; the thighs and upper arms behave as pendulums and the lower legs and forearms have whiplash movements. These swinging movements modify the boundary-layer.

Clark [14], using the Schlieren optical system, considered the air-flow patterns around moving limbs. Visualisation of the air flows around the legs of a runner have shown that the "pendulum effect" produces completely different flow patterns to those found in linear flows. The flow around a swinging thigh forms a bow wave and a trailing wake and these are alternately established and reversed by each change in direction of the swinging leg. The flows around the lower legs and forearms are similar in nature, although more complex.

Classical fluid dynamics and heat transfer theories are inappropriate for these conditions and that's because the movement of the body during walking and running is more complex than those associated with man-made structures on which the theory is based. Movement of the body through the air produces additional difficulties; an unidirectional air flow is superimposed on the alternating flows produced by the "pendulum effect".

Schlieren visualisation shows similar flows around swinging and translating heated cylinders which were used to simulate the action of the limbs during human movement.

Measurements of the local convective heat loss around the thighs of a runner on a treadmill were performed in a climatic chamber by Clark [6]. It has been demonstrated that, both in still air and in presence of wind, the distribution of a convective heat loss around the circumference of the thigh is different from that in an unidirectional airflow. Graphical integration was used to obtain a value for the overall heat transfer coefficient around the thigh. The coefficient was about twice as high as expected in a unidirectional wind equal to the mean velocity of the oscillating leg. A linear wind, representing the effect of shift of the body, further increased the convective heat loss.

A very important improvement of heat and mass transfer theory with liquid evaporation into a turbulent air stream was developed [15 - 17]. Particularly, for what concern the heat transfer by evaporative cooling with heat inputs from surroundings, it was obtained and critically analyzed the following empirical equation for the treatment of their experimental data:

$$Nu = C_2 R_e^{0.8} P_r^{0.33} G_u^{0.2} \tag{3}$$

Where the number of Reynolds is directly proportional to the fluid air velocity and G_u is the Gukhmann number equal to $(T_2 - T_1)/T_2$; it is important to note that the "heat transfer coefficient" which in classical theory of forced convection is independent on temperature, in turbulent convection with heat inputs depends not only on air velocity and density but also on skin and air temperature.

Dimensional Parameters

Because the differential equations of heat convection can only be solvable for simple geometries such as pipes or ducts, they are not valid for complex boundary conditions. Therefore, dimensional analysis helps to interpret heat transfer phenomena more easily after reorganizing and presenting the data in dimensionless form. Some of the most important dimensionless parameters for heat convections are following.

· ***Nusselt number***

In the case of a heat transfer within a fluid at a boundary surface, the Nusselt number is defined as the ratio of convective to conductive heat transfer normal to the boundary. The convection and conduction heat flows are parallel to each other and to the surface normal of the boundary surface, and are all perpendicular to the mean fluid flow in the simple case.

$$Nu = \frac{(Q/A)L}{k\Delta T} \tag{4}$$

where:

Q/A = thermal flux (W/m^2)

L = characteristic length of the body

k = thermal conductivity of the fluid

ΔT = temperature difference between the body and the surrounding fluid

Typically the average Nusselt number is expressed as a function of the Rayleigh number and the Prandtl number.

· ***Prandtl number***

The Prandtl number Pr is a dimensionless number approximating the ratio of the kinematic viscosity to the thermal diffusivity and it is defined as:

$$\Pr = \frac{v}{\alpha} = \frac{c_p \mu}{k} \tag{5}$$

where:

v = kinematic viscosity (m^2/s)

α = thermal diffusivity (m^2/s)

μ = viscosity (Pa s)

k = thermal conductivity (W/(m K))

c_p = specific heat (J/(kg K))

ρ = density (kg/m^3)

For air, Pr is approximately 0.7, depending slightly on temperature.

· ***Grashof number***

The mathematical expression governing the flow parameters of velocity and thickness is the Grashof Number. The Grashof number Gr is a dimensionless number in fluid dynamics and heat transfer which approximates the ratio of the buoyancy to viscous force acting on a fluid. It frequently arises in the study of situations involving natural convection and it is defined as:

$$Gr = \frac{g \beta \Delta T L^3}{v^2} \tag{6}$$

where:

g = acceleration due to gravity

β = thermal expansion coefficient

ΔT = temperature difference

L = length

v = kinematic viscosity

When the Grashof number is less than 2 x 10^9 the flow is laminar and closely follows the contours of the body. If the Grashof number exceeds 10^{10} the flow is fully turbulent; the region between these two values of the Grashof number is subject to transitional flow with the fluid having characteristics of both laminar and turbulent flow. For a naked standing man in an air temperature of 20^{o}C the flow remains laminar to a height of about 90 cm and only becomes fully turbulent after 150 cm [4].

Fig. 1 shows the variation of the Grashof number with vertical height over the body surface for a skin temperature of 33^{o}C and an ambient air temperature of 20^{o}C showing the regions of laminar, transitional and turbulent flow. The dotted area around the outline of the human figure indicates the convective boundary layer flow [4]. The free convective heat loss per unit area is directly dependent on the slope of the temperature profile within the boundary layer flow and may be expressed by $q = kdT / dX$, where k is the thermal conductivity of the air, and dT/dX is the slope of the temperature profile at the skin surface, with X the horizontal distance from the body surface.

In areas where the boundary layer is thin, the temperature gradient is steep and there is a consequent high heat loss. Where the layer is thicker, the temperature has a greater horizontal distance in which to drop from that of the skin to the surroundings, the gradient is, therefore, shallower and the heat loss lower.

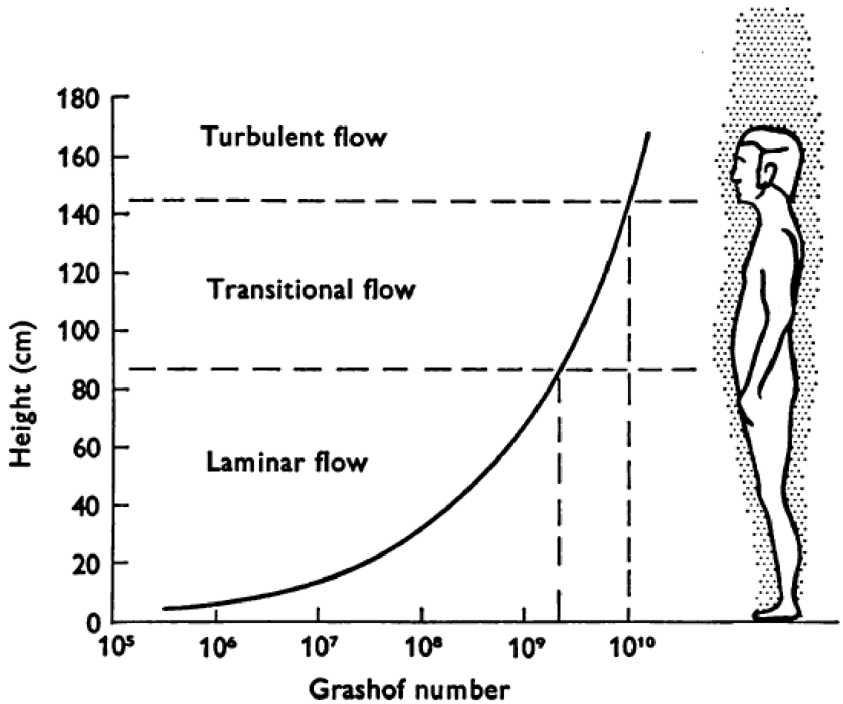

Figure 1 Variation of Grashof number with vertical height over the body surface.

In the case of the standing man the boundary layer affords a degree of thermal protection since the flow has been increasing in thickness over the body. Consequently the temperature gradients over the head are shallow and the convective heat loss is limited.

If the subject is lying down the flow pattern over the head is substantially different. In this posture there is no flow over the head from below, there is only the boundary layer which has been generated over the head itself. Because of these differences in flow fields it is to be expected that the local and total heat losses from the head may vary with changing body posture.

· ***Rayleigh number***

In the context of fluid mechanics, the Rayleigh number for a fluid is a dimensionless number associated with buoyancy driven flow (also known as free convection or natural convection). When the Rayleigh number is below the critical value for that fluid, heat transfer is primarily in the form of conduction; when it exceeds the critical value, heat transfer is primarily in the form of convection. The product, $Gr{\cdot}Pr$ is the Rayleigh number Ra which can be used to find the Nusselt number. As a result the Rayleigh number for free convection near a vertical wall is:

$$Ra_x = Gr_x \Pr = \frac{g\beta}{v\alpha}(T_s - T_\infty)x^3 \qquad (7)$$

where:

Ra_x = Rayleigh number

Gr_x = Grashof number

Pr = Prandtl number

g = acceleration due to gravity

x = characteristic length

T_s = surface temperature

T_∞ = quiescent temperature (fluid temperature far from the surface of the object)

v = kinematic viscosity

α = thermal diffusivity

β = thermal expansion coefficient

4.3 Radiation

Radiation refers to heat transfer by the emission of electromagnetic waves which carry energy away from the emitting body. The transfer of energy from the sun to the surface of earth is accomplished primarily by radiation. Radiation is also the mechanism contributing the most to heat loss from the human body.

In 1879, Josef Stefan experimentally determined a simple expression relating radiant emission from a surface to its temperature. Stefan's results were theoretically confirmed in 1884 by one of his former students, Ludwig Boltzmann. The resulting expression, known as Stefan-Boltzmann Law, states that the total radiant emission, integrated over all frequencies (or wavelengths), is proportional to the fourth power of its absolute temperature:

$$H = e\sigma AT^4 \qquad (8)$$

where:

e = emissivity (0-1)

σ = Stefan-Boltzmann constant = 5.67×10^{-8} J/(s-m^2-K^4)

A = surface area of object

T = Kelvin temperature

The linear radiation exchange satisfies the following equation:

$$\dot{R} = h_r \left(T_{sk} - T_r \right) \tag{9}$$

where T_{sk} is the skin temperature, calculated directly by thermography or by assigning determined factors to each of the thermocouple measurements (one every 30″) proportionally to the fraction of the body total surface area, represented by each specific area [7]:

$$\left(0.07head + 0.14arms + 0.05hands + 0.07feet + 0.013legs + 0.019thighs + 0.35trunk \right) \tag{10}$$

T_r represents the mean radiant temperature of the surrounding.

The heat transfer coefficient h_r takes the following form, as the physical process is regulated by the Stefan-Boltzmann law:

$$h_r = \sigma \varepsilon S\left(a\right) f \left(T_{sk}^3 + T_r T_{sk}^2 + T_r^2 T_{sk} + T_r^3 \right) \tag{11}$$

In Eq. 11, the term $S\left(a\right)$ is the 4π radiating area of the human body surface according to Dubois surface, and varies by posture: 0.70 in sitting position, 0.725 in standing position within +/- 2% regardless of height and body position [8]. With the presence of clothing, the radiating area of the body $S\left(a\right)$ increases by a factor *f*. Fanger, Breckenridge and Goldeman [7] have shown that *f* increases approximately 15% for each Clo.

All objects absorb and emit energy. Energy that is absorbed causes electrons to "jump" to a higher energy level; when electrons fall from a higher energy level to a lower one the energy that is lost is emitted as electromagnetic radiation. If the absorption of energy is greater than the emission of energy, the temperature of an object will rise (assuming no heat transfer mechanism other than radiation); if the absorption of energy is less than the emission of energy, the temperature of an object will fall. An object will reach its equilibrium temperature when the absorbed energy equals the emitted (radiated) energy.

Any object at a temperature larger than absolute zero will radiate energy to some extent and the quantity and quality (wavelength) of radiation depends solely on the temperature of the object. A conceptual model used to describe the relationship between body temperature and radiant energy is that of a blackbody.

4.3.1 Blackbody radiation

A blackbody absorbs all incident radiation irrespective of direction and wavelength. In addition to be a perfect absorber, a blackbody is also a perfect radiator. Therefore, all radiation leaving a blackbody is emitted by the surface and no surface can emit more energy than a blackbody, Fig. 3. In addition, a black surface is a diffuse emitter, i.e. the emitted radiation is a function of the wavelength and temperature but independent of the direction.

In 1900, Max Planck found an expression describing the spectral distribution of the radiation intensity from a blackbody, known today as Planck's Law*:*

$$E_{\lambda,b}\left(\lambda,T\right)=\frac{C_1\lambda^{-5}}{\exp\left(C_2/\lambda T-1\right)} \tag{12}$$

where C_1 =3.742 x 10^8 W $\mu m^4/m^2$ is the first radiation constant, and C_2 =1.4389 x 10^4 µm K is the second radiation constant.

Fig. 2 shows the Planck's distribution for different representative temperatures: from the Cosmic Microwave Background (CMB) radiation, to the emitted surface temperature of a Blue Star (the most energetic kind of star at about 40,000 K). Also shown in this graph, is the Planck distribution for the Sun's surface temperature (5,800 K), for a common incandescent light bulb temperature (3,000 K), for the minimum temperature at which an object will glow in the visible spectrum (~800 K) and for a 0^oC blackbody (273.15 K).

Some interesting observations can be retrieved from this graph: (1) emitted radiation continuously varies with the wavelength; (2) the total amount of emitted energy increases with temperature; (3) the peak of the curve shifts to the lower wavelength end of the spectra; (4) there is more energy difference per degree at shorter wavelengths.

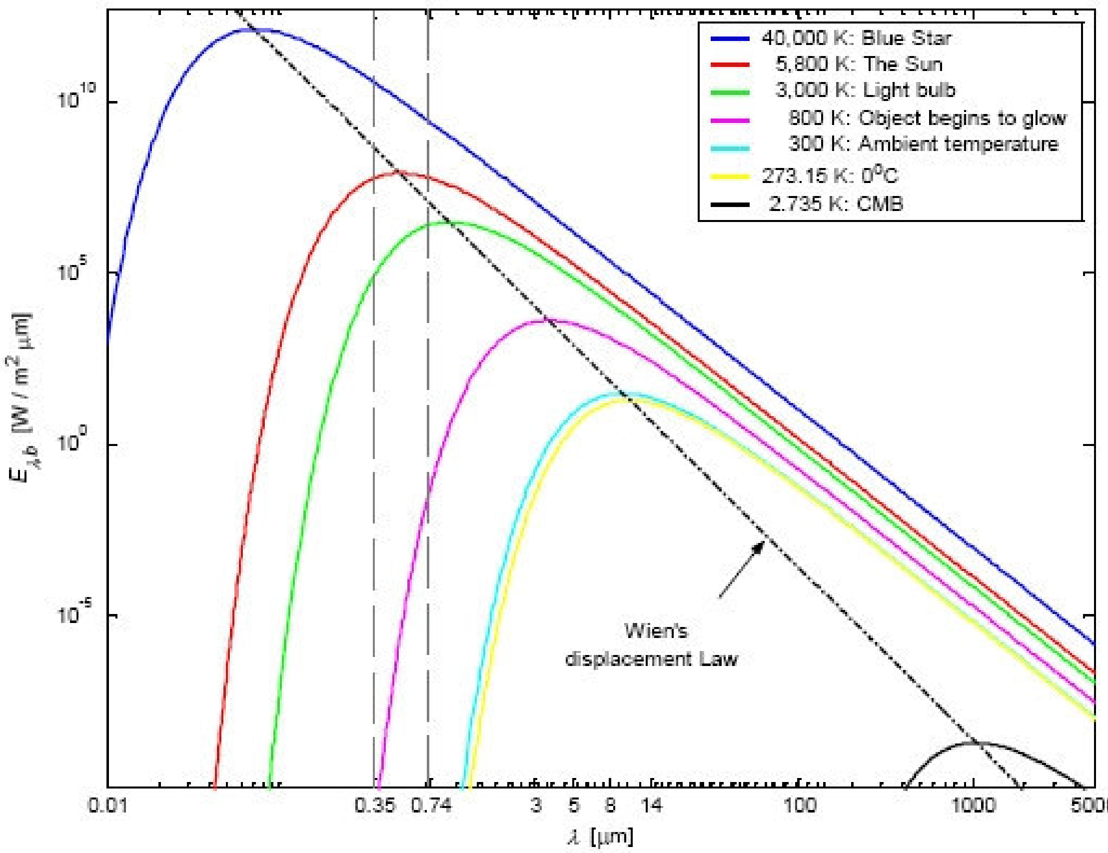

Figure 2 Planck's distribution at different temperatures.

Planck's Law gives the intensity radiated by a blackbody as a function of frequency (or wavelength), whilst Stefan- Boltzmann's Law gives the total flux integrated over all frequencies (or wavelengths). Now, the frequency (or wavelength) at which Planck's distribution has the maximum specific intensity is given by Wien's displacement Law. In 1893, Wilhelm Wien measured the spectral distributions for a blackbody at different temperatures. Wien found that the peak energy was proportional to their corresponding wavelength for varying temperature, that is:

$$\lambda_{\max} T = C_3 \tag{13}$$

where C_3 =2897.8 μm K, is the third radiation constant. This relationship can be obtained by differentiation of Eq. 12 with respect to λ, and setting the result equal to zero.

Wien's Law gives an indication of the 'colour' of the thermal radiator.

Planck's law is an invaluable tool to estimate spectral distribution for a blackbody, which corresponds to the theoretical maximum possible emission from any real object.

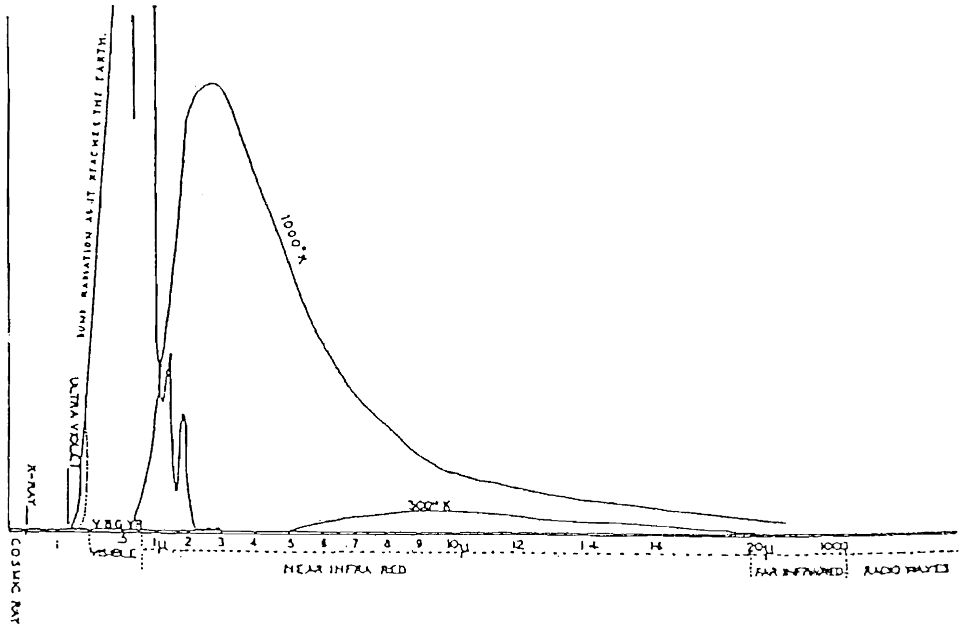

Figure 3 Spectral distribution of radiation from the sun, stove and the human body (From Hardy, 1934).

4.3.2 Surface emission

· **Emissivity** ε

Emissivity ε is defined by Kirchhoff, as the ratio of thermal radiation emitted by a real surface at a given temperature to that of a blackbody at the same conditions (temperature, wavelength and direction):

$$\varepsilon(\lambda, T_S) = \frac{E(T_S)}{E_b(T_S)} \tag{14}$$

This relationship represents an average over all possible directions and wavelengths and can be used, together with Planck's distribution law, Eq. 12, to compute the emissive power. Hence, spectral distribution for real surfaces does depend on the wavelength but it differs from Planck's Law distribution shown in Fig. 2.

Four types of sources can be distinguished according to their spectral emissivity variations: a blackbody (perfect radiator), for which $\varepsilon(\lambda,T_S)=\varepsilon=1$; a graybody for which $\varepsilon(\lambda,T_S)=\varepsilon=constant<1$; a whitebody (perfect reflector), for which $\varepsilon(\lambda,T_S)=\varepsilon=0$; and a selective radiator, for which $\varepsilon(\lambda,T_S)$ varies with λ.

The value of emissivity tends to vary from one material to another. With metals a rough or oxidised surface usually has a higher emissivity than a polished surface. In Table 3 there are some examples of emissivity values.

Table 3 Emissivity values.

Material	Emissivity
Steel polished Steel oxidises	0.18 0.85
Brass polished Brass oxidised	0.10 0.61
Aluminium polished Aluminium oxidised	0.05 0.30
Cement and Concrete	0.90
Asphalt	0.90
Red Brick	0.93
Graphite	0.85
Cloth	0.85

Gaertner and Goepfert [7] investigated the radiation characteristics of live human skin and they found that the radiation coefficient of the skin ε for the back of the human body is equal to 0.960, for the forearm is equal to 0.960 and for the sole of the foot is 0.941.

· **Absorptivity *α***

Absorptivity is a property of the body surface and is dependent on the temperature of the body and the wavelength of the incident radiation. It is a dimensionless value and measured as the fraction of incident radiation that is absorbed by the body. For a blackbody $\alpha=1$, whilst $\alpha=0$ corresponds to a whitebody. For real surfaces, absorptivity range between 0 and 1. More formally, the ratio of radiant emission from a real surface E, to absorptivity α, is a constant for all materials equal to the incident radiant energy to a surface or irradiation G, at the same temperature T_S , that is:

$$\frac{E(T_S)}{\alpha} = G \qquad (15)$$

Absorptivity depends on direction and wavelength, but is practically unaffected by surface temperature.

· **Reflectivity *ρ***

The fraction of the incident radiation reflected by a real surface is defined as reflectivity. Even though reflectivity depends on the direction of both, the incident and reflected radiation, it is convenient to work with integrated average to avoid complication. If a surface reflects radiation in all directions regardless of the direction of the incident radiation, the surface is said to be diffuse. Conversely, if radiation is reflected with an angle equal to the incident angle, the surface is specular. Absorptivity and reflectivity are responsible for our perception of colour. As discussed above, colour is not the result of emission, since only objects at high temperature (higher than ~800 K) glow in the visible portion of the spectra. Instead, colour is the result of a balance between reflection and absorption. A surface is white if it reflects all incident radiation, and it is black if it absorbs all the irradiation in the visible spectra. Colour, however, does not give an indication of the absorbed or reflected irradiation since most of the energy may be in the IR band. The typical example is the snow, which is highly reflective at visible wavelengths (between 350 and 750 nm), but strongly absorbs and emits IR radiation, approximating a blackbody at longer wavelengths.

· **Transmissivity τ**

The ratio of the directly transmitted radiation after passing through a participating medium (atmosphere, dust, fog) to the amount of radiation that would have passed the same distance through a vacuum is defined as transmissivity. Dissolved colloidal and suspended particles cause further attenuation by absorbing and scattering the incident light beam. Higher attenuations are observed at long wavelengths. Transmissivity is of importance when selecting the spectral band of operation of the IR equipment.

· **Energy balance**

In active thermography applications (see Chapter 10), we are interested in capturing the emissions coming from a surface following an external excitation. However, not all the incident energy is re-emitted by the surface as depicted in Fig. 2. On the contrary, one part of the energy is absorbed, one part is transmitted. In addition, not all the emitted energy is the result of the active thermal excitation. Part of the energy that is being emitted by a surface is the reflection from several external sources, other than the active thermal excitation, and another part is energy coming form the inside.

As a result, surface emission is a complex process resulting from a balance between transmission, absorption, and reflection.

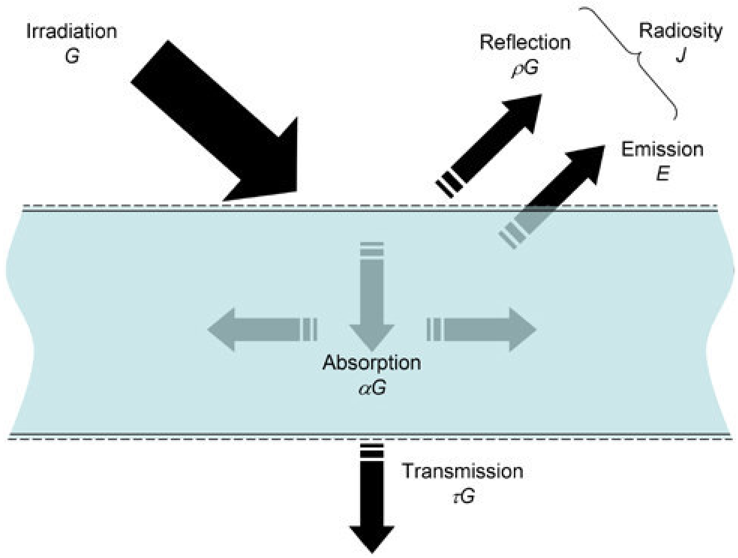

Figure 4 Energy balance in a semitransparent medium.

As illustrated in Fig. 4, a fraction of irradiation *G* is absorbed *αG*; another fraction is reflected *ρG*; and for semitransparent media, another fraction is transmitted through the surface *τG*. Symbols *α*; *ρ*; and *τ*.; correspond to the absorptivity, the reflectivity and the transmissivity, respectively, which are the surface properties defined below. By the energy conservation principle:

$$G = \alpha G + \rho G + \tau G \quad (16)$$

it follows that:

$$\alpha + \rho + \tau = 1 \quad (17)$$

For opaque materials *τ=0,* from Eq.17, therefore:

$$\varepsilon = (1 - \rho) \quad (18)$$

which is convenient when reflectance is easier to measure than emissivity.

As seen in Fig. 4, Radiosity *J*, is the sum of two contributions: direct emissions from a surface *E*, and reflected irradiation from the incident ray *ρG*. For a blackbody however at a given temperature: $G=E_b$, when combined with Eq. 14 and Eq. 15, it follows that:

$$\varepsilon = \alpha \quad (19)$$

which is commonly referred as Kirchhoff's Law.

4.3.3 Electromagnetic spectrum

All matter regardless of its state or composition continuously emits electromagnetic radiation. Radiation can be viewed either as the transportation of tiny particles called photons or quanta; or as the propagation of electromagnetic waves.

The energy from a heated object is radiated at different levels across the electromagnetic spectrum. In most industrial applications it is the energy radiated at infrared wavelengths which is used to determine the object's temperature. Fig. 5 shows various forms of radiated energy in the electromagnetic spectrum including X-rays, Ultra Violet, Infrared and Radio. They are all emitted in the form of a wave and travel at the speed of light. The only difference between them is their wavelength which is related to frequency. Gamma Rays and X-Rays are widely used in medicine, security and nondestructive testing. On the other hand, wavelengths ranging from 1 mm to several hundred meters, right part of Fig. 5, are transparent to the atmosphere, so they are mostly used for data transmission, e.g. radio, TV, mobile phones, etc. Many other kinds of waves used in numerous applications are enclosed between these two extremes.

Whenever there is a thermal difference (above 0 K) between two objects, radiation will be exchanged in the form of heat. The thermal radiation band is enclosed between 0.1 and 1000 μm of the spectrum (highlighted in Fig. 5). The thermal spectrum can be divided into three spectral bands: the ultraviolet (UV) spectrum, the visible band and the infrared (IR).

The infrared part of the spectrum (0.74 - 1000 μm) can be further subdivided into five parts: Near Infrared (NIR) from 0.74 to 1 μm; Short Wavelength Infrared (MIR) from 1 to 3 μm; Medium Wavelength Infrared (MWIR) from 3 to 5 μm; Long Wavelength Infrared (LWIR) from 8 to 14; and Very long Wavelength Infrared (VLWIR) from 14 to 1000 μm.

Infrared radiation is invisible to the unaided eye, hence, energy radiated in the IR band needs to be transformed into a visible image through specialized imaging equipment.

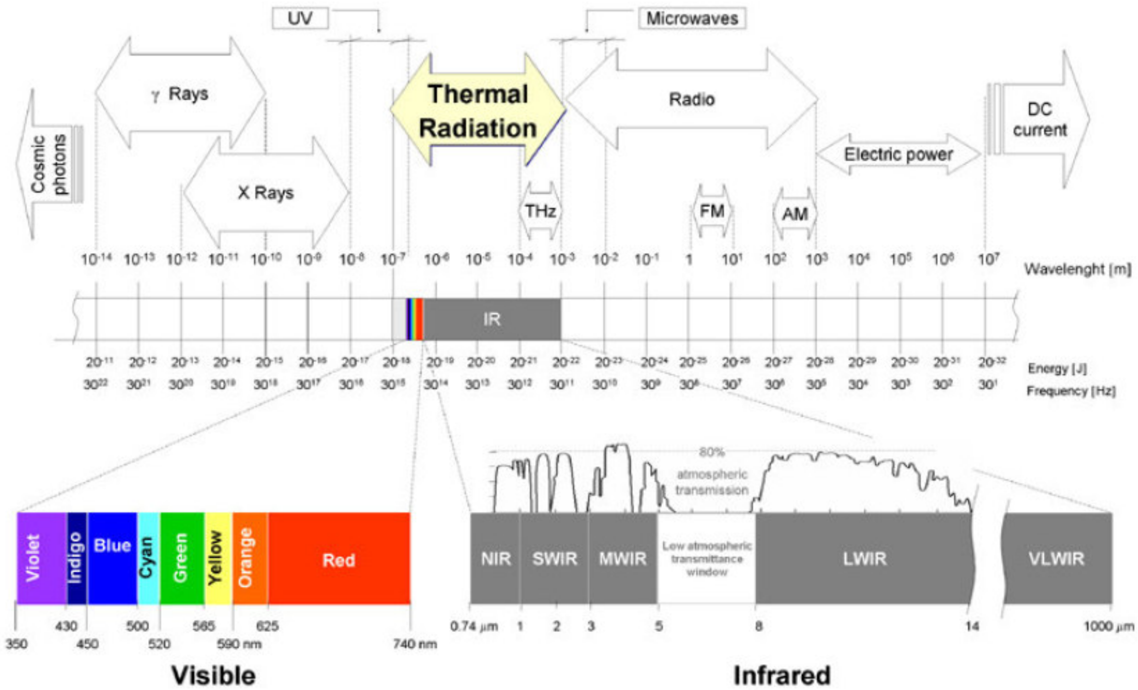

Figure 5 The Infrared region of the Electromagnetic spectrum.

4.4 Respiration

Respiration is the oxygen and carbon dioxide gas exchange between the atmospheric air and the tissues. Nose, pharyngeal area, trachea and bronchi don't participate in gas exchange. However they play an important role in warming the inspired air to the body temperature and saturate it with water vapour.

In the respiratory system, the separation of aerosols takes place in the alveolar area and is defined basically by three processes, i.e., diffusion, inertial separation (rebound effect) and sedimentation. Table 4 shows the diameter, the surface and the volume of the sections of the respiratory system based on Landahl's model [7] and on the following respiratory conditions: minute volume = 15 l. min^{-1}, respiratory frequency = 15 min^{-1}.

Respiration combines the processes of evaporation (of moisture in the lungs) and convection (displacement of warm air in the lungs by cold air from the outside environment). Convective heat exchange by the lungs depends both on the pulmonary ventilation and the temperature difference between the expired and ambient air.

Table 4 Model of lungs during the inspiration phase (proposed by Landahl, supplemented by Jacobi), [7].

Region	Number	Diameter (cm)	Length (cm)	Surface (cm^{-2})	Volume (cm^{-3})	Function type
Trachea	1	1.6	12	60	24	Conductive zone with cilia epithelium
Main bronchi	2	1.0	6	40	10	
Lobar bronchi	12	0.4	3	45	5	
Segmental br.	100	0.2	1.5	100	5	
Subsegmental br.	800	0.15	0.5	200	10	
Terminal br.	$6 \cdot 10^4$	0.06	0.3	3400	50	
Respiratory br.	$2 \cdot 10^5$	0.05	0.15	4700	60	Respiratory zone with alveoli
Alveolar duct.	$5 \cdot 10^6$	0.04	0.05	30000	300	
Alveolar sacc.	$5 \cdot 10^7$	0.04		250000	2500	
(Inspiration condition connected to a lung volume of 3000 cm^3)						

It has been demonstrated [10 - 12] that cold air blown on the skin or other cold stimulation of the face elicits reflex bronchoconstriction in both patients with respiratory diseases and in non-asthmatic subjects. Sensory receptors in the nasal cavity, pharynx, larynx, face and trunk may mediate these reflexes. Cold also has direct effect on airway smooth muscle [13]. An increase of evaporative heat loss from the airways to the environment may contribute to the symptoms observed in asthmatics after breathing cold air. The air is capable to contain only very small amounts of water at low temperature. Saturated air contains 2.4 g water per m^3 air at -10°C, which is about 10% of the water content of air at body temperature. Inhaled air is humidified by evaporation from the mucosal surface [3].

4.5 Evaporation and diffusion through skin

Two different modes of diffusion are responsible for the exchange of matter between organisms and the surrounding air. Molecular diffusion operates within organisms (e.g. in the lungs of the human body) and in a thin skin of air forming the boundary layer that surrounds the whole organism. In the free atmosphere, transfer processes are dominated by the effects of turbulent diffusion, although molecular diffusion continues to operate and is responsible for the degradation of turbulent energy into heat.

Mass transfer to or from objects suspended in a moving airstream is analogous to heat transfer by convection and is conveniently related to a non-dimensional parameter similar to the Nusselt number of heat transfer theory. This is the Sherwood number *Sh* defined by the following equation:

$$F = ShD\left(X_s - X\right)/d \qquad (20)$$

where:

F = mass flux of a gas per unit surface area ($gm^{-2}\ s^{-1}$)

X_s, X = mean concentration of gas at the surface and in the atmosphere ($gm^{-2}\ s^{-3}$)

D = molecular diffusivity of the gas in air ($m^2\ s^{-1}$)

So, we can have:

$$Sh = \frac{F}{D\left(X_s - X\right)/d} \qquad (21)$$

The Sherwood number can be defined as the ratio of actual mass transfer *F* to the rate of transfer that would occur if the same concentration difference were established across a layer of still air of thickness *d*.

Evaporation is associated with the relative humidity. A high relative humidity will slow the ability of the body to lose heat by evaporation because the air is already holding a great deal of water vapour or moisture, and it is difficult for the air to absorb more. When the relative humidity is too low, the dry air absorbs moisture off the skin at a high rate and the skin is dried out. The skin cracks, flakes and in extreme cases bleeds.

The humid heat loss (H_{humid}) accounts for the latent heat of sweat evaporated at the skin surface and transported as vapour through clothing and air layers. The equation for the humid heat loss is:

$$H_{humid} = \frac{P_s - P_a}{R_c} \qquad (22)$$

where:

P_s = the actual, average water vapour pressure at the skin surface

P_a = the ambient water vapour pressure, expressed in Pascal

R_c = the resistance to evaporative heat transfer by clothing and air layers.

The efficiency of cooling by sweat depends on the rate of evaporation *E*, which is determined by the gradient between the vapour pressure of the wetted skin (e_{sk}) and the partial pressure (vapour pressure) of water vapour in the ambient air (e_a), multiplied by a root function of effective air velocity at the skin surface (*V*) and the fraction of body surface that is wetted.

At high levels of e_a or low air velocities, the fraction of the body surface that is wetted increases until the body is completed wetted. Any further increase in sweat production does not contribute to cooling because the liquid perspiration drips off the body and is wasted as a coolant. The passage from “insensible perspiration” to “sensible” one is assumed to be between 29 ºC and 30 ºC as mean skin temperature.

The equation that correspond to Sherwood number for vapour transfer in turbulent air stream is the following:

$$Sh = C_3 R_e^{0.8} S_e^{0.33} G_u^{0.2} \tag{23}$$

If we consider that e_{sk} is the vapour pressure at the skin surface, e_a is the vapour pressure in the air and *p* is the air pressure, so the gradient of virtual temperature is:

$$\frac{T_{sk} - T_a}{T_a} = \frac{T_{sk}\left(1 + 0.38\left(e_{sk} / P\right)\right) - T_a\left(1 + 0.38\left(e_a / P\right)\right)}{T_a\left(1 + 0.38\left(e_a / P\right)\right)} \tag{24}$$

The importance of vapour pressure term, when T_{sk} is close to T_a can be illustrated in the case of the human body covered with sweat at 33 ºC and surrounded by still air at 30 ºC and 20% relative humidity.

Considering the mass flow and substituting the atmospheric pressure with the ratio between molecular weight gas constant, and temperature it is possible to write the evaporation cooling equation:

$$E = C_3 \frac{2165 S_a D}{L_a T_{sk}} \frac{\lambda\left(e_{sk} - e_a\right) R_e^{0.8} S_c^{0.33}}{T_{va}^{0.2}} \left(T_{vsk} - T_{va}\right)^{1.2} \tag{25}$$

This term account the corresponding flux of latent heat which comes from evaporation of sensible perspiration.

At normal skin temperature, the evaporation of 1 litre of sweat requires 2.4 MJ (580 kcal). The magnitude of the sweat loss may be estimated simply by weighting the subject nude or dressed in dry clothing, before and after the experiment, and by weighting food and fluid ingested and stools and urine voided during the period of observation. Furthermore, weight loss due to respiratory gas exchange should be included in the calculation, and may be accounted for as follows [2]:

$$C_{g_e} = \dot{V}_{o_2}\left(1.977 \cdot R - 1.429\right) \qquad (26)$$

where:

C_{g_e} = weight loss in g·min^{-1} due to respiratory gas exchange

$\dot{V}_{o_2}$ = oxygen uptake in litres·min^{-1} STPD

R = respiratory quotient

1.977 = weight in g of 1 litre CO_2 STPD

1.429 = weight in g of 1 litre O_2 STPD

Such measurements are valid for the calculation of heat balance only as long as all the sweat produced during the experiment is actually evaporated. On the other hand, whether the produced sweat is evaporated or part of it has run off the body, the sweat rate is an indication of the magnitude of the heat stress.

References – Chapter 4

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CHAPTER 5

Evolution of the heat exchange equation

Numerous models have been developed, including the Pennes model, to understand how blood flow and skin conductivity are related.

The Pennes model has been adapted by many researchers for the analysis of a variety of bioheat transfer phenomena. As more scientists have evaluated the Pennes model for application in specific physiological systems, it has become increasingly clear that many of the assumptions foundational to the model are not valid. For example, Chato [6], Chen and Holmes [7], and Weinbaum, et al. [8-19, 32] all demonstrated very convincingly that thermal equilibration between perfused blood and local tissue occurs in the precapillary arterioles and that by the time blood flows into vessels 60μm in diameter and smaller, the equilibration process is complete. Therefore, no significant heat transfer occurs in the capillary bed; the exchange of heat occurs in the larger components of the vascular tree.

Many investigators have developed alternative models for the exchange of heat between blood and tissue. These models have accounted for the effects of vessel size [6, 3, 20], countercurrent heat exchange [20-24], as well as a combination of partial countercurrent exchange and bleed-off perfusion [8-19, 29].

All of these models provided a larger degree of rigor in the analysis, but at the compromise of greater complexity and reduced generality. Some of these models have been the subject of considerable debate concerning their validity and range of appropriate application [25-28]. These studies also led to an increased appreciation of the necessity for a more explicit understanding of the local vascular morphology as it governs bioheat transfer, which has given rise to experimental studies to measure and characterize the three dimensional architecture of the vasculature in tissues and organs of interest.

5.1 The Pennes model

Pennes [2] published the major work on developing a quantitative analysis between arterial blood and tissue temperature. His work consisted of a series of experiments to measure temperature distribution as a function of radial position in the forearms of nine human subjects. A butt-junction thermocouple was passed completely through the arm via a needle inserted as a temporary guideway, with the two leads exiting on opposite sides of the arm (Fig. 1).

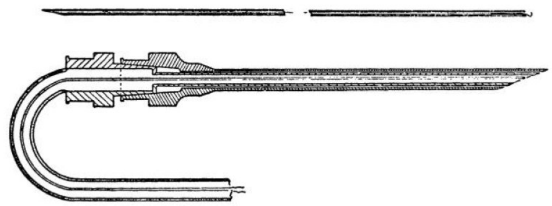

Figure 1 Top: 26 – Gauge stainless steel needle used for introduction of Y-model thermocouple. Needle contains steel wire coated with varnish and baked in place. Loop at the end of wire receives lead wire of thermocouple which is knotted in place. **Bottom:** Brachial artery thermocouple, built in a 24-gauge hypodermic needle with insulated junction in bevel of needle [2].

The subjects were unanesthetized so as to avoid the effects of anaesthesia on blood perfusion. Following a period of normalization, the thermocouple was scanned transversely across the mediolateral axis to measure the temperature as a function of radial position within the interior of the arm. The environment in the experimental suite was kept thermally neutral during experiments. Pennes' data showed a temperature differential of three to four degrees between the skin and the interior of the arm, which he attributed to the effects of metabolic heat generation and heat transfer with arterial blood perfused through the microvasculature.

Pennes proposed a model to describe the effects of metabolism and blood perfusion on the energy balance within tissue. These two effects were incorporated into the standard thermal diffusion equation, which is written in its simplified form as:

$$\rho c \frac{\partial T}{\partial t} = \nabla k \nabla T + (\rho c)_b \, \omega_b (T_a - T) + q_{met} \qquad (1)$$

Metabolic heat generation, q_{met}, is assumed to be homogeneously distributed throughout the tissue of interest as rate of energy deposition per unit volume. It is assumed that the blood perfusion effect is homogeneous and isotropic and that thermal equilibration occurs in the microcirculatory capillary bed. In this scenario, blood enters capillaries at the temperature of arterial blood, T_a, where heat exchange occurs to bring the temperature to that of the surrounding tissue, T. There is assumed to be no energy transfer either before or after the blood passes through the capillaries, so that the temperature at which it enters the venous circulation is that of the local tissue. The total energy exchange between blood and tissue is directly proportional to the density, ρ_b, specific heat, c_b, and perfusion rate, ω_b, of blood through the tissue, and is described in terms of the change in sensible energy of the blood. This thermal transport model is analogous to the process of mass transport between blood and tissue, which is confined primarily to the capillary bed.

A major advantage of the Pennes model is that the added term to account for perfusion heat transfer is linear in temperature, which facilitates the solution of Eq. 1.

Assuming the venous blood temperature equilibrates with the tissue temperature and that the metabolic heat is uniform in time and space, the Pennes bioheat transfer equation in spherical coordinates is given by:

$$\rho bcb\frac{\partial V_b}{\partial t} = kb\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial V_b}{\partial r}\right) + \frac{A + Bt^{-1/2}}{\frac{4}{3}\pi a^3} \qquad r < a \qquad (2)$$

$$\rho mcm\frac{\partial Vm}{\partial t} = k_m\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial V_m}{\partial r}\right) - wc_{bl}V_m \qquad r > a \qquad (3)$$

The limitations of this model arises from the invalid view of the heat transfer process and its anatomical location. Chen and Holmes' analysis of blood vessel thermal equilibration lengths showed that Pennes' concept is incorrect [3]. The thermal equilibration length is defined as the length at which the difference between the blood and tissue temperature decreases to 1/e of the initial value. They indicated that thermal equilibration occurs predominantly within the terminal arterioles and venules, and that blood is essentially equilibrated prior to the capillaries. In considering the contribution of perfusion as a non-directional term, the directional convective mechanism is neglected. Nor does the model account for specific vascular architecture such as counter-current arteries and veins. The limitations of Pennes model have motivated subsequent investigators to develop their own models.

Despite its incorrect concept, the perfusion term of Pennes model has been widely used, and found to be valid for situations other than the forearm. Its wide usage has been mainly due to its simplicity of implementation, especially in analyses where a closed form analytical solution is sought [4, 5].

5.2 The Weinbaum - Jiji model

In 1979, Weinbaum and Jiji [12] proposed the initial model of the artery-vein pair as two parallel cylinders of equal diameters with collateral bleedoff in the plane normal to the cylinders. The anatomical configuration is a schematic of an artery and vein pair with branches to the peripheral skin layer (Fig. 2). The contribution of perfusion to heat transfer in tissue was treated as heat transfer in a porous medium.

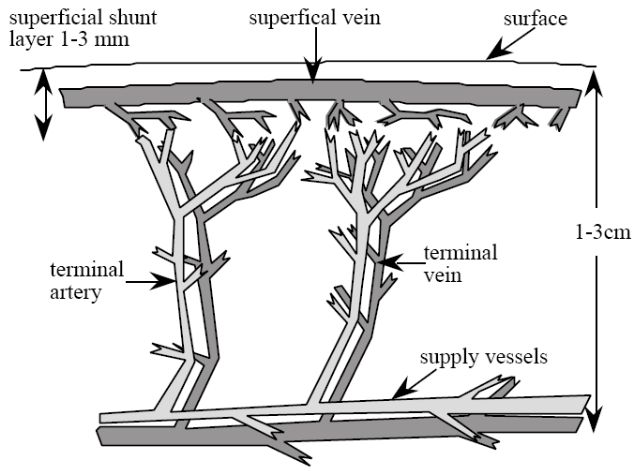

Figure 2 Schematic of Artery and Vein Pair in Peripheral Skin Layer [43].

It was considered as a unidirectional convective term normal to the artery-vein pair. Knowledge of vessel density, diameter, and blood velocity was required at the different blood vessel generations.

In 1984, they presented a more thorough model based upon anatomical observations with Lemons [8, 9]. This model analyzed three tissue layers of a limb: 1) deep, 2) intermediate, and 3) superficial or cutaneous. For the counter current structure of the deep tissue layer, they proposed a system of three coupled equations:

$$(\rho c)_b \pi r_b^2 \bar{V} \cdot \frac{dT_a}{ds} = -q_a \tag{4}$$

$$(\rho c)_b \pi r_b^2 \bar{V} \cdot \frac{dT_V}{ds} = -q_V \tag{5}$$

$$\rho c \frac{\partial T}{\partial t} = \nabla k \nabla T + ng\,(\rho c)_b \cdot (T_a - T_v) - n\pi r_b^2 (\rho c)_b \bar{V} \cdot \frac{d(T_a - T_v)}{ds} + q_m \tag{6}$$

The first two equations (Eq. 4-5) describe the heat transfer of the thermally significant artery and vein, respectively. The third equation (Eq. 6) refers to the tissue surrounding the artery-vein pair. For this equation, the middle two right-hand side terms represent the capillary bleed-off energy exchange, and the net heat exchange between the tissue and artery-vein pair, respectively. The capillary bleed-off term is similar to Pennes' perfusion term except the bleed-off mass flow (g) is used. Their analysis showed that the major heat transfer is due to the imperfect counter-current heat exchange between artery-vein pairs. They quantified the effect of perfusion bleed-off associated with this vascular structure, and showed that Pennes' perfusion formulation is negligible due to the temperature differential.

One of the limitations of this model is the difficulty of implementation, and that the artery and vein diameters are identical.

In response to the criticism that their model is difficult and complex to apply, Weinbaum and Jiji simplified the three equation model to a single equation (Eq. 7).

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_{eff} \frac{\partial T}{\partial x} \right) + q_{met} \tag{7}$$

In their simplification, they derived an equation based on the temperature of tissue only. The imperfect counter-current heat exchange is embodied in an effective conductivity tensor term.

$$k_{eff} = k \left\{ 1 + \frac{n\left[(\rho c)_b \pi r_b^2 \bar{V} \cos\gamma \right]}{\sigma_\Delta \cdot k^2} \right\} + q_{met} \tag{8}$$

The k_{eff} term has similar parameters to the tissue and artery-vein pair heat exchange term in Eq. 8, and a shape factor term (σ_Δ).

An obvious limitation of this model is that the local temperatures along the counter-current artery and vein cannot be calculated [1].

5.3 The Charny - Levin model

Charny and Levin proposed a one-dimensional "three equation model" [30], similar to the Wissler model [29], which comprised the local temperature in the arteries, in the veins and in the tissue in the direction of blood flow using three separate heat balance equations.

Thus they proposed a bioheat transfer model which calculate the spatial variations in the arteriole, venal, and muscle temperatures in a human extremity under both resting and hyperthermic conditions connected with a realistic circulatory system.

The human body is lumped into 17 body segments; each body segment is subdivided into six layers: core, muscle, fat, skin, artery and vein. The model is characterised by a single temperature throughout the body at a given time. Each tissue element is characterised by its temperature, volume, surface area, density, specific heat, thermal conductivity, basal metabolic rate, basal evaporation rate, basal blood perfusion per unit volume of tissue and electrical conductivity.

The blood compartment is characterised by a single temperature, volume, density and specific heat. The central blood compartment is divided into an abdomen and pelvis segment. There are a total of 102 elements in the model of the human body: 68 tissue elements and 34 blood elements. Each blood element is characterised by its volume, specific heat, density and electrical conductivity. Arterial and venous blood flows through each segment via a large vessel which exchanges heat with the surrounding tissue. This tissue corresponds to the muscle layer except the thorax, abdomen, neck, and head in which the large artery and vein are both assumed to be embedded in the core tissue.

Heat exchange in the pulmonary circulation is modelled separately by considering the lungs and the heart as part of the lumped thoracic. The effect of temperature on skin blood flow and sweating is modelled based on the work of Stolwijk and Hardy [31] which predicts with reasonable accuracy, the dynamic thermoregulatory responses to dynamic loads of ambient temperature and internal heat production even during a very heavy exercise.

Results of the proposed model show that even when the paired arteriole and venule are assumed to have equal radii, the mean temperature under both steady and transient conditions is not equal to the mean of the arteriole and venule blood temperatures. Tissue temperature profiles during hyperthermia computed with the three-equation model are similar in shape and magnitude to those predicted by the traditional one-equation Pennes bioheat transfer model. This is due primarily to the influence of thermoregulatory mechanism in the heated muscle. The unexpected agreement is significant given the inherent relative simplicity of the traditional Pennes model.

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CHAPTER 6

Simulation of the energetic consumption by a mathematical model

In thermophysiology the key instrument for dissipating the internal heat surplus is given by the increase of the peripheral blood flow which, by changing the conductivity of the muscle tissues, alters the emission-dispersion characteristics of the “skin radiant”.

The problem of human external body heat exchange is usually tackled determining both the independent variables in human thermal environment and the physiological “dependent” variables and subsequently applying an experimental modified heat transfer theory [1, 2].

6.1 The Sacripanti model

Generally, the energy expenditure of an athlete is measured by indirect calorimetry since it is not possible to use direct calorimetry. Sacripanti et al [3] studied the energy expenditure of an athlete during competition considering the athlete as a complex thermal machine. Consequently a new model was developed for the evaluation of the heat exchange between the human body and the environment.

It was assumed that the application of the principles of thermodynamics consent to measure statistically the average work of an athlete during exercise. Hence the idea is to perform a direct calorimetry through an energy equation which describes the heat exchange.

In particularly, the heat exchange by respiratory system was studied through the theoretical thermodynamics using non dimensional groups. A body immersed in a fluid loses heat through a laminar boundary layer of uniform thickness, then the heat waste per unit area can be written as:

$$C = h_c\left(T_{sk} - T_a\right) = \frac{K}{\delta}\left(T_{sk} - T_a\right) \tag{1}$$

where:

K = thermal conductivity of the fluid

δ = thickness of the boundary layer

T_{sk} = mean skin temperature

T_a = ambient temperature

Eq. 1 was used to describe the heat loss by forced or by free convection from an object with a mean surface temperature T_{sk} surrounded by a fluid in T_a even though the boundary layer is neither laminar nor uniformly thick. In that case, δ is the thickness of an equivalent rather than a real laminar layer. It is determined by the size and geometry of the surface and by the way in which fluid circulates over it.

A more useful form of Eq. 1 can be derived by substituting a characteristic dimension of the body *d* for the equivalent boundary layer thickness, which cannot be measured directly. Then the Eq. 1 becomes:

$$C = \frac{d}{\delta} K \left(T_s - T \right) / d \qquad (2)$$

The ratio d/δ is the Nusselt number.

In forced convection, the Nusselt number depends on the rate of heat transfer through a boundary layer from a surface, hotter or cooler that the air passing over it; a process analogous to the transfer of momentum by skin friction. As a result the Nusselt number is a function of the Reynolds number and the ratio of boundary layer thickness for heat (t_H) and for momentum (t_M). This ratio is a function of the Prandtl number defined by (v/k). Measurements of heat loss by forced convection from planes, cylinders and spheres can be described by the general relation:

$$Nu \propto \mathrm{Re}^n \, \mathrm{Pr}^m \qquad (3)$$

Where *m* and *n* are experimental constants and $t_M / t_H = \mathrm{Pr}^m$.

The convective exchange by the lungs is function of frequency of breathing and of air quantity inspired. Because we have different values of lung ventilation at different levels of activity, the better way to obtain the convective stream is to define an “effective cylindrical surface” of the lungs. Obviously it depends on the “tidal volume” of the athlete at rest or during exercise. The effective surface may range from 0.05 m^2 at rest, up to 0.103 m^2 during maximal exercise.

The experimental points characterizing heat transfer lie on a straight line of the well-known “critical relation”:

$$Nu = C_1 \, \mathrm{Re}^{0.8} \, \mathrm{Pr}^{0.33} \qquad (4)$$

This experimental form of Nusselt number gives us the final following relation:

$$\dot{C} = nC_1 \frac{K_a S_p}{L_p} R_e^{0.8} P_r^{0.33} \left(T^* - T_a \right) \qquad (5)$$

where:

- n is the breath frequency value: 3 at rest, 4 for light exercise, 5 for heavy exercise, 10 for maximal exercise.
- Sp is the effective surface of the lungs
- Lp is the mean diameter of the lung
- T^* is the internal temperature of the lung equal to the body core temperature
- Ta is the ambient temperature
- Ka is the thermal conductivity of the fluid

For what concern the heat exchange by convection it was considered a modified Gukhmann number. Thus a new convective heat exchange equation was developed with the following form:

$$\dot{C}_c = C_2 \frac{K_a S_a}{L_a} \frac{R_e^{0.8} \mathrm{P}_r^{0.33}}{T_a^{0.2}} \left(T_{sk} - T_a\right)^{1.2} \tag{5}$$

Furthermore, the convection term of the proposed equation is multiplied by a factor of the form: $\alpha = \left(e^{T-30}\right)$

For what concern the evaporation cooling equation it was proposed the following equation:

$$E = C_3 \frac{2165 S_a D}{L_a T_{sk}} \frac{\lambda\left(e_{sk} - e_a\right) R_e^{0.8} S_c^{0.33}}{T_{va}^{0.2}} \left(T_{vsk} - T_{va}\right)^{1.2} \tag{6}$$

This term accounts the corresponding flux of latent heat which comes from evaporation of sensible perspiration. But not all the quantity of sweat which produced is evaporate. Based on Kobayashi's [4] research for the percentage of sweat evaporated, it is possible to introduce a new term which takes into consideration the percentage of evaporated sweat form the skin, in upright position, which may be raise in the range of 63 to 65%.

On this basis the terms of convective and diffusive heat loss, which account for evaporative cooling, should be multiplied by the following factor:

$$\left\{ e^{\frac{0.06 \lambda P_a - \Sigma\{C_c + E\} t}{0.12 \lambda P_a}} - 1 \right\} \tag{7}$$

Finally, joining together the four processes, Sacripanti's equation takes the following integral form:

$$\dot{Q}t = S_a f \sigma\varepsilon\left(T_{sk}^4 - T_a^4\right) + nC_1 \frac{K_a S_p}{L} R_e^{0.8} P_r^{0.33}\left(T^* - T_a\right) +$$

$$\left\{\left[e^{(T\Delta - 30)}\right]\left[C_2 \frac{K_a S_a}{L_a} \frac{R_e^{0.8}\,\mathrm{P}_r^{0.33}}{T_a^{0.2}} (T_{sk} - T_a)^{1.2}\right] + \right.$$

$$\left.\left[C_3 \frac{2165 S_a D}{L_a T_{sk}} \frac{\lambda\left(e_{sk} - e_a\right) R_e^{0.8} S_c^{0.33}}{T_{va}^{0.2}} (T_{vsk} - T_{va})^{1.2}\right]\right\} \tag{8}$$

$$\left\{e^{\frac{0.06\lambda P_a - \Sigma\{C_c + E\}t}{0.12\lambda P_a}} - 1\right\}$$

At first place, it was developed a code in FORTRAN based on the Sacripanti's equation for the simulation of the energy expenditure of the athlete. Figure 1 displays the flowchart used for the development of the code. Then, a new and improved code was developed in Labview based always on the same model for the purpose of this study.

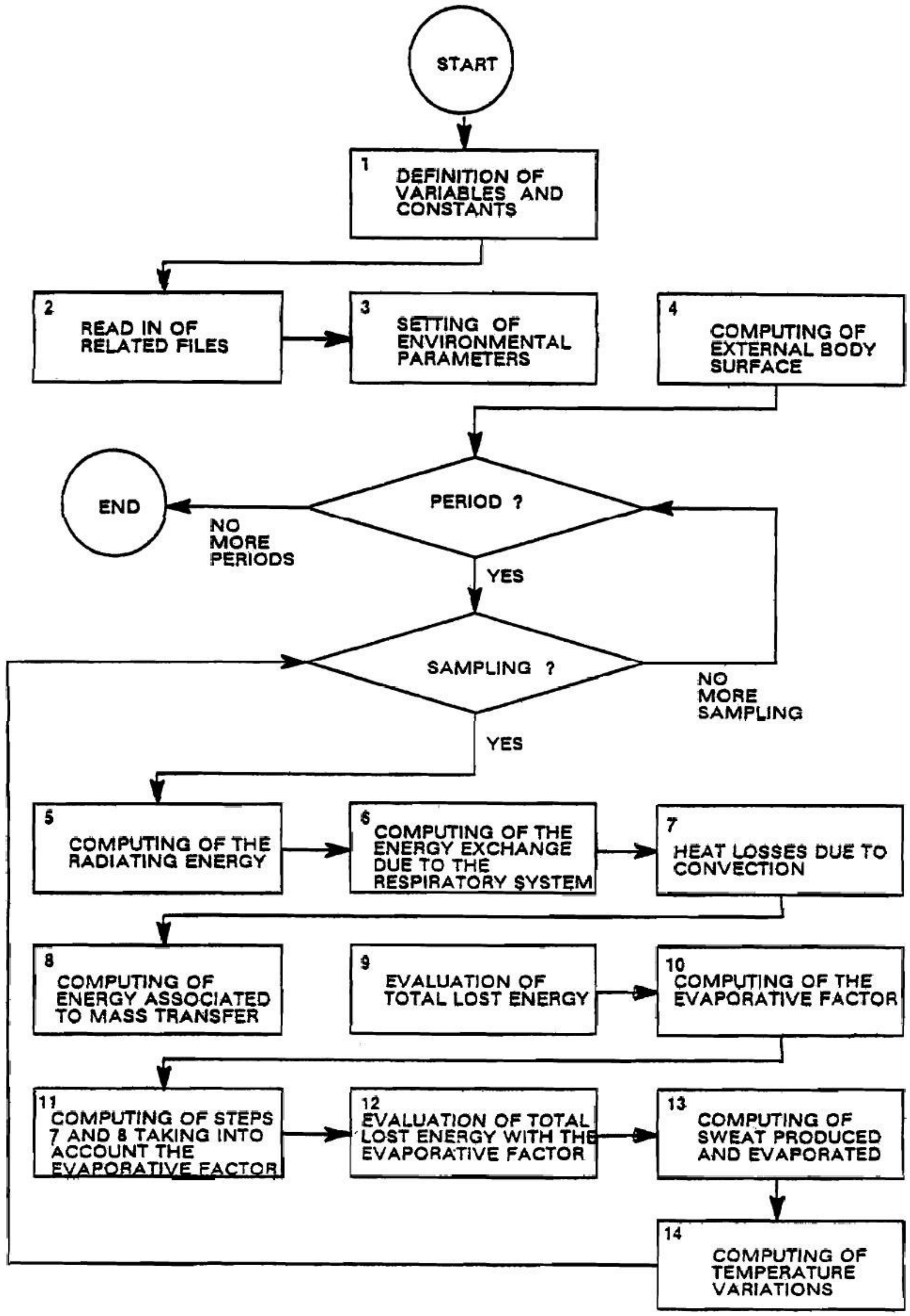

Figure 1 Flowchart of the code in FORTRAN for the simulation of the energy consumption of an athlete.

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CHAPTER 7

Whole-body Vibration

Vibrations are present in many situations of everyday life. Vibrations arise when a body moves back and forth due to external and internal forces. In the case of whole-body vibration *(WBV)*, it may be the seat of a vehicle or the platform on which a worker is standing that vibrates, and this motion is transmitted into the body of the driver.

We can be exposed to vibration in work, commuting between home and work, in leisure travelling; basically in any situation where we are moving. In practice it is almost impossible to avoid vibration exposure in modern society. The number of mechanized sources of vibrations have increased and the number of exposed persons has risen. Additionally, the quality of life becomes more important. The vibration exposure in daily life is usually around or a bit higher than the perception threshold. For example, not only health aspects are important components of the acceptability of a vehicle but also the discomfort caused by seat as well as the interior sound has become important over the last years. The benefit of better information and knowledge about the perception of vibrations and the human response to vibrations allows to improve designs so that comfort would increase and the annoyance experienced from excessive vibrations would be reduced.

7.1 Introduction

The human body is exposed to various kinds of vibrations, which are transmitted by different parts into the body, e.g., in vehicles, in aircrafts, by hands, feet, backside etc. These different sensations of vibrations can be separated into two big sections, the perception of whole-body vibration and the perception of hand-arm transmitted vibration.

Hand-arm vibration (HAV) is the transfer of vibration from a tool to a worker's hand and arm. The amount of HAV is related to the acceleration level of the tool when grasped by the worker and in use. The vibration is typically measured at the handle of the tool while in use to determine the acceleration levels transferred to the worker.

Whole-body vibration refers to mechanical energy oscillations which are transferred to the body as a whole, usually through a supporting system such as a seat or platform. Typical exposures include aircrafts (e.g. helicopters), driving automobiles and trucks, and operating industrial vehicles. Thus whole-body vibrations occur when the human body (standing, lying, sitting) is in contact with a vibrating surface.

Oscillations in the frequency range from 1 to 80 Hz (and sometimes higher) are called vibrations in existing standards (e.g., ISO 2631-1, 1997; VDI 2057-1, 1987). Movements with frequencies below 1 Hz are denoted as motions and the excitation with such low frequency movements produce motion sickness. The perception of whole-body vibrations is often coupled with the hearing of low-frequency sound (sound below 20 Hz is called infrasound) because a vibrating structure or surface usually emits sound, as well.

Human response to whole-body vibration is a very complex phenomenon. Several extensive surveys have been conducted to summarize the effects on the human being and it can be concluded that responses are diverse (Damkot et al 1984, Frymoyer et al 1993, Hulshof & Zanten 1987, Sandover 1991, Seidel & Heide 1986).

Whole-body vibration can be divided in two subtypes depending on the variation with time, deterministic or stochastic [29]. Deterministic vibration is further divided into periodic or non-periodic. The simplest type of periodic vibration is sinusoidal. The stochastic vibration is not predictable and is also named noise. Continuous vibration with small variation in amplitude is named stationary. A shock-type vibration (transient) is non-stationary and may appear during a short period with high amplitude [29].

Most experimental and laboratory studies on the acute effects of whole-body vibration exposure have been done using a simulator with one d.o.f. The type of applied vibration has been short-term, sinusoidal in the vertical direction although with varying magnitudes and frequencies. Thus, most conclusions based on laboratory studies refer to relatively simple vibration conditions and short-term effects. For observational studies, aiming at describing the whole-body vibration exposure during work and long-term health effects, the methodological problem has been to exactly state vibration doses. Various estimates of the true vibration dose are normally utilized.

A review of whole-body vibration characteristics associated with low back disorders/problems is summarized in Table 1. From the review it seems as if the most critical direction for low back pain is the z-direction, i.e. vibration in the vertical plane. Less is known about other vibration measurements than the root mean square of the acceleration (r.m.s) in relation to musculoskeletal symptoms.

Table 1 Vibration characteristics for earth moving vehicles, associated with lower back disorders/problems.

Author/Year	Type	r.m.s-magnitude (ms^{-2})	Range (ms^{-2})	Direction	Dominant direction	Dominant frequency (Hz)
Johanning 1991	Subway cars	0.55	0.32-0.99	Vector sum	z-axis	2.5, 12.5
Boshuizen et al./1992	Freight-container tractors	1.04	-	Vector sum	z-axis	2.5, 3.15
Boshuizen et al./1992	Fork-lift trucks	0.80	-	Vector sum	x- and z-axis	1.6, 2.5
Bovenzi&Zadani/1992	Busses	0.40	0.18-0.65	z-axis	z-axis	-
Bovenzi&Betta/1994	Tractors	1.22	0.89-1.47	Vector sum	-	-
Malchaire et. al/1996	Fork-lift trucks	1.59	0.39-3.80	z-axis	z-axis	4.5

7.2 Vibration axes

Human are able to discriminate six different kinds of vibrations which are specified in ISO 2631-1 (1997) and VDI 2057-2: three translational directions, that means vibrations in x-, y- and z-direction (basicentric axis), as well as three rotational directions: around the x- (roll), the y- (pitch) and the z-axis (yaw). The basicentric axes are defined according to the orientation of the body with respect to gravity (Fig. 2). For a seated person, motions in the x-axis are back to front or fore-and-aft [5]. Motions in the y-axis are right to left or lateral. Motions in the z-axis are from foot to head or vertical (Griffin 1990). Griffin states that rotational motion always produces some translation at all points other than the centre of rotation [6].

Fig. 1 shows an anatomical and basicentric coordinate system for measurement of hand–arm vibration exposure as defined in ISO 5349-1 (2001).

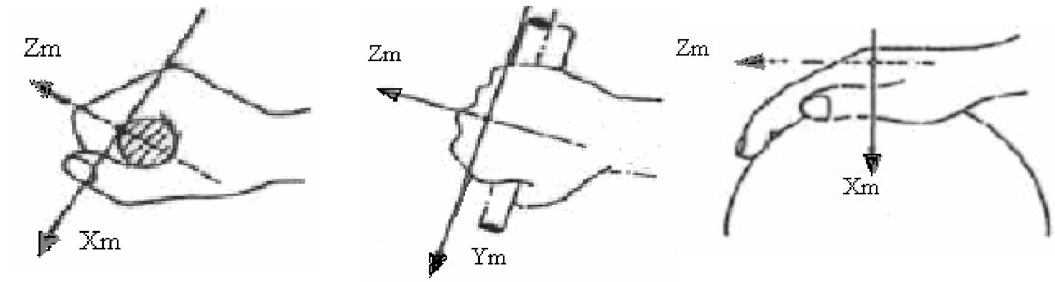

Figure 1 Basicentric coordinate system for hand-arm vibrating system.

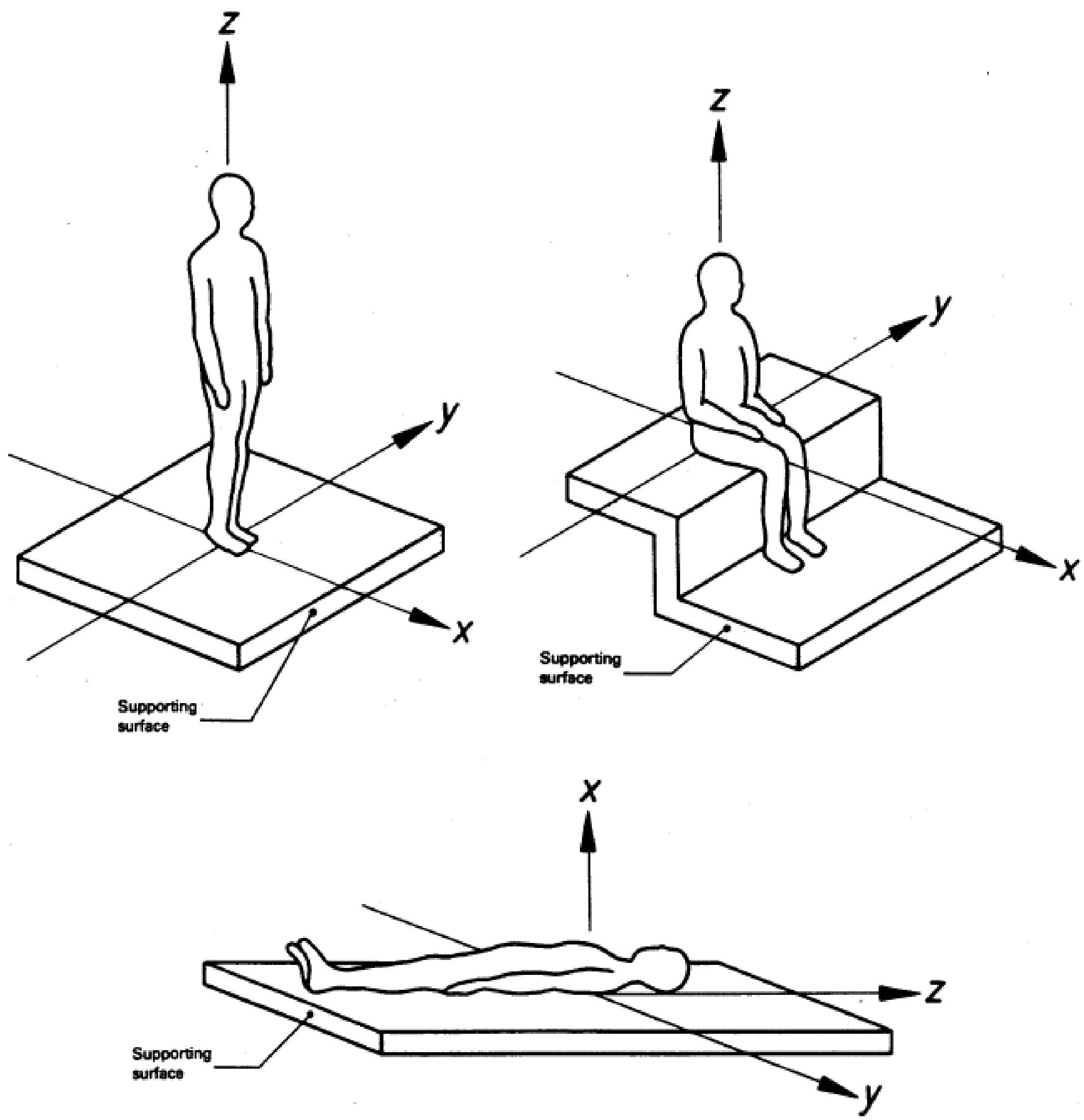

Figure 2 The orientation of the basicentric axes to the gravitational field, specified in, e.g., ISO 2631-1 (1997); VDI 2057-2 (1987).

7.3 Frequencies of whole-body vibration

Frequency represents the number of times per second the vibrating body moves back and forth (see Chapter 2). It is expressed as a value in cycles per second, more usually known as hertz.

The human body can be compared to a mechanical structure and like all other mechanical structures it has specific frequencies where the joining parts exhibit a maximum mechanical response. This resonance appears at different frequencies for different parts. All people response differently to whole-body vibrations because of their variations in physique and posture. Two mechanical responses of the body are often used to describe the manner in which vibration causes the body to move: transmissibility and impedance.

Transmissibility $T(f)$ is defined as the ratio of the acceleration at a point on the body $a_{body}(f)$ to the acceleration at the seat $a_{seat}(f)$ at frequency f:

$$T(f) = \frac{a_{body}(f)}{a_{seat}(f)} \qquad (1)$$

The transmissibility indicates to which extent the vibration is transmitted from the seat through the body and is highly dependent on the vibration frequency. Although a vibration input is vertical it causes an output at e.g. the head in several axes. This phenomenon is called cross axis forces. Nawayseh et al [4] reported that cross axis forces in the fore-and-aft direction appears on the seat and backrest during exposure of subjects to vertical vibration.

Most research on the transmissibility of the human body has investigated the relation between vertical vibration of a seat and the resulting vertical vibration at the head. Studies so far reported have found only a weak correlation between vertical head motion and discomfort. The person who is made most uncomfortable by a motion is not necessarily the individual with the highest transmissibility [6]. The transmissibility of the whole body is usually determined between the seat surface (as an input) and the head (as an output). Measurements to other locations on the surface of the body have occasionally been reported: to the hip [24], shoulder [25], thorax [26], and cervical vertebrae [27].

An additional term to whole-body vibration is the mechanical impedance of the body. This term is often used as a generic term for all relations between the driving force of a system at a particular frequency and the resultant movements (acceleration, velocity, displacement) at that frequency. More specifically the driving-point mechanical impedance, Z(f), is defined as the ratio of the driving force, F(f), acting on a system to the resulting velocity, v(f), of the system measured at the same point and in the same direction as the applied force:

$$Z(f)=\frac{F(f)}{v(f)} \tag{2}$$

The mechanical impedance of a body gives some indication of what force is required to produce a given movement and can be used to indicate internal resonances in a structure. In the case of human body, as a structure, it might indicate those frequencies of vibration to which the body is most sensitive, mechanically.

The most commonly used impedance measures are the 'driving point mechanical impedance', 'apparent mass' and 'absorbed power'. The quantity apparent mass has the advantage that it can be obtained most directly from the signals provided by accelerometers and force transducers. When the human body is effectively rigid (for example, at very low frequencies in the vertical axis) the apparent mass of the body is equal to its static mass and the force and acceleration are in phase. As the frequency increases, one or more resonances increase the apparent mass and there is an increasing phase difference between the force and the acceleration [6].

The apparent mass can be defined as:

$$M(f)=\frac{F(f)}{a(f)} \tag{3}$$

Where *M(f)* is the apparent mass, *F(f)* is the force and *a(f)* is the acceleration at frequency *f*.

In the frequency domain, the apparent mass can be calculated using the cross spectral density (CSD) method defined by:

$$H(f)=\frac{G_{io}(f)}{G_{ii}(f)} \tag{4}$$

Where $G_{io}(f)$ is the cross spectral density between the acceleration and the force, and $G_{ii}(f)$ is the power spectral density of the acceleration.

Holmlund [3] showed that mechanical impedance, normalized by the sitting weight, varies with direction, level, posture and gender. Generally the impedance spectra show one peak for the fore-and-aft (*X*) direction while two peaks are found in the lateral (*Y*) direction. Males showed a lower normalized impedance than females. Increasing fore-and-aft vibration decreases the frequency at which maximum impedance occurs but also reduces the overall magnitude. For the lateral direction a more complex pattern was found. The frequency of impedance peaks are constant with increasing vibration level. The magnitude of the second peak decreases when changing posture from erect to relaxed. Males showed a higher impedance magnitude than females and a greater dip between the two peaks. The impedance spectra for the two horizontal directions have different shapes.

Many experimental studies in the laboratory use sinusoidal vibrations or excitations to investigate the human response to vibration because it is easy to produce such vibrations and the description of the vibration signals is possible with simple parameters. Additionally, it is possible to study the response to a single frequency of motion with a sinusoidal excitation. In practise, not only periodic narrow band and sinusoidal vibrations occur but also vibration exposures with broadband signals to random characteristics are often encountered during work, travel and leisure time. These signals are also stochastic and they contain transient events sometimes, especially in a passenger cabin in a vehicle. The fact that, the human body is more sensitive for random, stochastic vibrations is frequently reported in the literature [30, 31]. The interest frequency ranges vary according to the environment and the effect. Effects of whole-body vibrations on health, activities, perception and comfort is often associated with frequencies from 1 to 100 Hz. At lower frequencies the principal effect of the oscillation is a kind of motion sickness. Above 100 Hz the sensitivity of the human body decreases because of physiological reasons. Additionally, the human ear gets more and more sensitive for stimuli with increasing frequency. That is the reason why vibrations and sounds emitted from vibrating surfaces are mostly perceived as audible cues for frequencies above 100 Hz, respectively. The degree to which vibration is transmitted to the human body depends on many factors, especially on the vibration frequency or on the weight of the subject who is sitting on a cushioned or a rigid seat.

Vibrations between 2.5 and 5 Hz generate strong resonance in the vertebra of the neck and lumbar region. If the body experiences vibration between 4 and 6 Hz, this energy can manifest itself in the trunk with amplification of up to 200%. Vibrations between 20 and 30 Hz can cause resonance between the head and shoulders. These situations can cause chronic musculoskeletal stress or even permanent damage to the effected region. It is interesting to note that in the longitudinal direction, that is feet to head, the human body is most sensitive to vibration in the frequency range 4 to 8 Hz. While in the transverse direction, the body is most sensitive to vibration in the frequency range 1 to 2 Hz. According to the standard, ISO 2631-1 (1997), analysis of the influence on health should be performed within the frequency range 0.5 to 80 Hz.

Frequency weighting *curves* are used to represent human perception of vibration. They convert measured acceleration signals into perceived acceleration signals, Fig. 3. These curves define the values by which the vibration magnitude at each frequency is to be multiplied in order to "weight" it according to its effect on the body. The weighting has a high value at frequencies of greater importance and low values at frequencies which have little effect. Frequency weightings

are therefore the inverse of equivalent comfort contours: where the contour is low the weighting is high. A weighting has a different shape according to whether it is applied to measures of the vibration displacement, velocity or acceleration.
It is assumed that frequency weightings for human response to vibration are dimensionless and, therefore, that frequency-weighted acceleration has unit of ms^{-2} r.m.s.

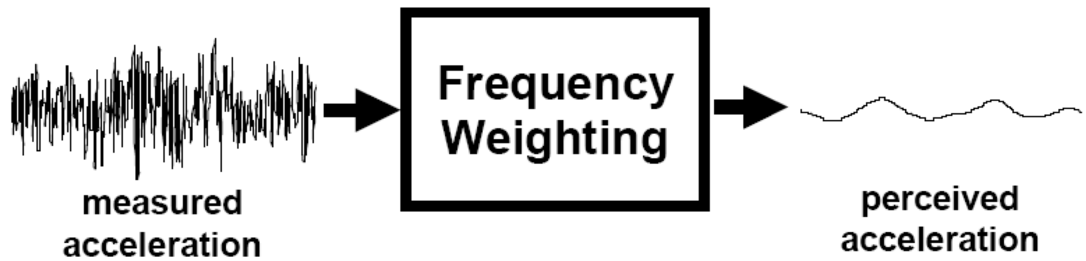

Figure 3 The frequency weighting filters convert acceleration signals into perceived acceleration signals.

Different frequency weightings are required for the different axes of the body. The frequency weighting curves for principle and additional weightings are show in Fig. 4. Two principle frequency weighting are used; W_k for the z direction and W_d for the x and y directions. Some special cases require additional frequency weightings. One example is seat-back measurements, W_c.

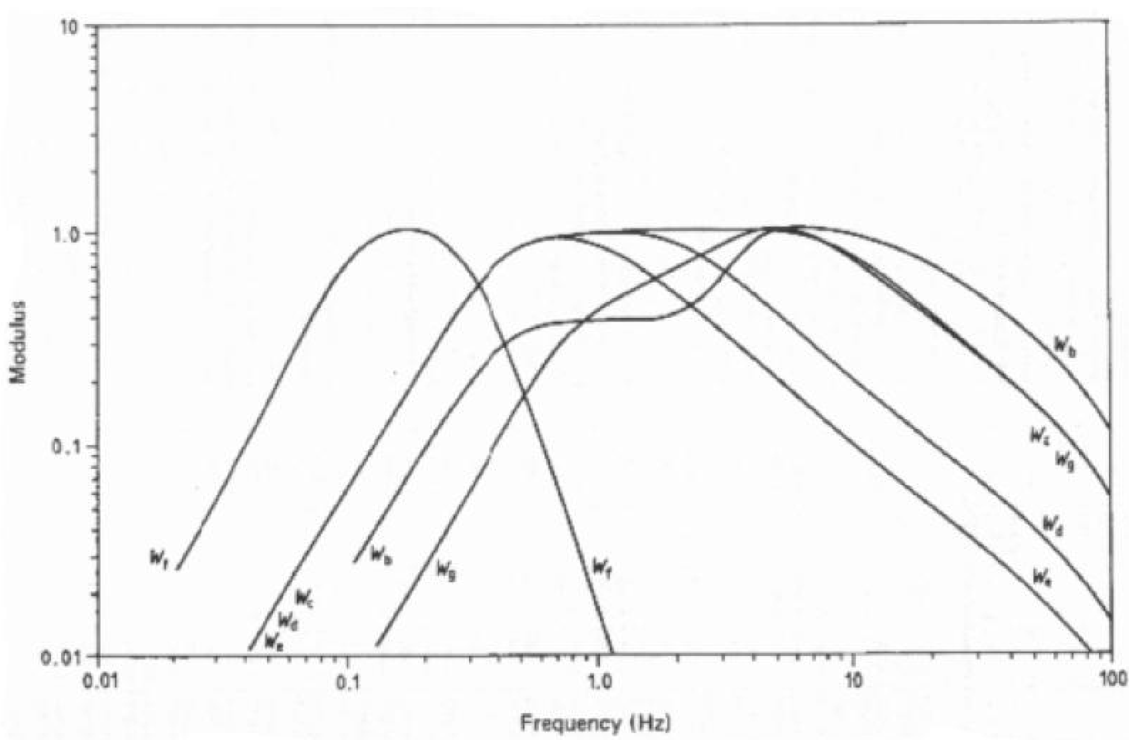

Figure 4 Frequency weighting curves for principal and additional weightings.

Tables 2 and 3 summarise which frequency weighting applies to which direction.

Table 2 Guide for the application of frequency weighting curves for principal weightings, ISO 2631-1: 1997.

Frequency	Health	Comfort	Perception	Motion Sickness
W_k	z-axis, seat surface	z-axis, seat surface z-axis, standing vertical recumbent (except head) x-,y-,z-axes, feet (sitting)	z-axis, seat surface z-axis, standing vertical recumbent	-
W_d	x-axis, seat surface y-axis seat surface	x-axis, seat surface y-axis, seat surface x-, y-axes standing horizontal recumbent y-, z-axes, seat back	x-axis, seat surface y-axis, seat surface x-, y-axes, standing horizontal recumbent -	-
W_f	-	-	-	vertical

Table 3 Guide for the application of frequency weighting curves for additional weighting factors, ISO 2631-1: 1997.

Frequency Weighting Factor	Health	Comfort	Perception	Motion Sickness
W_c	x-axis, seat back	x-axis, seat back	x-axis, seat back	-
W_e	-	r_x-, r_y-, r_z- axes, seat surface	<I r_x-, r_y-, r_z- axes, seat surface	-
W_j	-	vertical recumbent (head)	vertical recumbent	-

7.4 Magnitudes of whole-body vibration

The extent of the oscillation determines the magnitude of vibration. Magnitude can be quantified by displacement, velocity, and acceleration (see Chapter 2). For practical reasons, the magnitude of vibration is usually described by its acceleration.

The magnitudes generally of interest with whole-body vibration are contained with a 1000: 1 range form about 0.01 to 10.0 ms^{-1} (peak). Whole-body vibration with a peak magnitude below about 0.01 ms^{-1} will rarely be felt; at frequencies below 1 Hz and above about 20 Hz higher magnitudes are required for perception. Higher magnitudes are also required for perception of vibration by the fingers and other local parts of the body. Whole-body vibration with a magnitude of 10 ms^{-2} r.m.s may reasonably be assumed to be hazardous. Depending on the frequency, direction and duration of the vibration there may be some hazard associated with vibration magnitudes of about 1 ms^{-2} r.m.s. [6]

The evaluation of a vibrating signal is possible in the time domain or in the frequency domain. In the time domain an analysis points out parameters like: peak value, standard deviation, root mean square value (r.m.s), running R.M.S, crest factor, energy equivalent R.M.S, estimated Vibration Dose Value (eVDV), root-mean-quad value (rmq) or Vibration Dose Value (VDV). The evaluations and weightings in the frequency domain can be realized via a Fast Fourier Transformation (FFT) or in the power spectrum. The most important parameters are summarized in Tab. 4. Whereas the period T_s of the vibration time signal with a frequency f_s is sampled with $N=T_s{\cdot}f_s$ values for $x(i)$.

Table 4 Most relevant parameters for vibration time signals (adapted from Meloni 1991).

Parameter	**Definition**
mean	$\bar{x} = \frac{1}{N}\sum x(i)$
standard deviation	$\tau = \left[\frac{1}{N}\sum\left[x(i)-\bar{x}\right]^2\right]^{\frac{1}{2}}$
root-mean-square	$\text{r.m.s} = \left[\frac{1}{N}\sum x^2(i)\right]^{\frac{1}{2}}$
crest factor	$\frac{peak\ value}{r.m.s}$
root-mean-quad value	$r.m.q = \left[\frac{1}{N}\sum x^4(i)\right]^{\frac{1}{4}}$
Vibration Dose Value	$VDV = \left[\frac{Ts}{N}\sum x^4(i)\right]^{\frac{1}{4}}$
Estimated Vibration Dose Value	$eVDV = \left[\left(1.4(r.m.s)\right)^4 Ts\right]\frac{1}{4}$

Not only the physical variable like magnitude and frequency are important but also exogenous variables: e.g., posture and body-size of the subjects, exposure and endogenous variables: e.g., age and gender have influence on the perception of vibrations [7].

For periodic vibration and stationary random vibration the r.m.s. frequency-weighted acceleration often provides a sufficiently useful indication of the relative severities of different motions.

The r.m.s acceleration is not useful if the crest factor of a given transient vibration signal is high because the human body is more sensitive to changes in the vibration signal. Furthermore, the r.m.s value does not exceedingly point out the peaks in a signal. Instead of the r.m.s value the running r.m.s value $a_w(t_0)$, Eq. 5 is used with short durations τ if transient vibrations occur:

$$a_w\left(t_0\right)=\left[\frac{1}{\tau}\int_{t_{0-\tau}}^{t_0} a_w^2\left(t\right)dt\right]^{\frac{1}{2}} \qquad (5)$$

Or the Vibration Dose Value VDV, sometimes called fourth-power vibration dose, which is more sensitive for peak values, is used if high peak values occur in the vibration signal (like shock conditions):

$$VDV=\left[\int_0^T a_w^4\left(t\right)dt\right]^{\frac{1}{4}} \qquad (6)$$

The VDV is a method of assessing the cumulative effects (i.e. dose) of vibrations. If the crest factor is low (i.e. less than 6.0), the estimated Vibration Dose Value (eVDV) is sometimes used to calculate the approximate vibration dose value from the r.m.s of the frequency-weighted accelerations ($a_{r.m.s}$) and the exposure time t in seconds:

$$eVDV=1.4\cdot a_{rms}\cdot t^{\frac{1}{4}} \qquad (7)$$

When more than one stimulus is presented the total VDV must be calculated from the fourth root of the sum of the fourth powers of individual vibration dose values:

$$VDV_{total}=\left[\sum_i VDV_i^4\right]^{\frac{1}{4}} \qquad (8)$$

As with r.m.s. and peak measures, the acceleration must be frequency weighted before determining the r.m.q. or VDV. The r.m.q. value is intended for the comparison of motions which contain high peak values but can be quantified over a fixed period of time; the motions either have similar durations or different samples of the same motion yield similar values. The VDV is offered as a robust method of assessing the severity of all motions (deterministic or random, stationary or non-stationary, transient or shock) which are above the threshold of perception and fall within the frequency range of the analysis method. The VDV yields the equivalent magnitude of a 1s exposure to the motion.

7.5 Duration of whole-body vibration

It is expected that if a high magnitude of vibration occurs for less time, any adverse effect on comfort, activities or health will be reduced. The degree to which a reduction in magnitude will be beneficial depends on the relation between vibration magnitude and the adverse reaction as well as the relation between vibration duration and the adverse reaction. For some criteria a rapid reduction in magnitude may be appropriate with increases in duration, while for others there will be little need for any reduction in magnitude.

The simplest time dependency in current use involves a "fourth power" relation between acceleration, a, and exposure time, t (i.e. $a^4t=constant$). This relation appears to be provide reasonable conclusions when used to assess vibration conditions with a wide range of magnitudes and durations [6].

Health risk assessments are primarily based on the magnitude of vibration and duration of exposure (EU 2002, ISO 2631-1 1997). Exposure to vibration is proposed to be assessed over an 8 h period by measuring or calculating the daily vibration exposure (ISO 2631-1 1997, EU 2002). Most studies have measurement periods shorter than 8 h due to technical difficulties to store large amounts of data. Usually a selected representative period of the work is assessed and then extrapolated. Vibration exposure in epidemiological studies should thus be considered as estimates of the true daily occupational vibration exposure [5].

There are some attempts to obtain quantitative relationships between discomfort and exposure time. For example, Miwa [8] considered the relative discomfort produced by short periods of sinusoidal vibration and pulsed sinusoidal vibrations with various pulse shapes having durations up to 6s. He confirmed that discomfort increased with increasing duration up to some limit and suggested that beyond about 2s for vibration in the range 2-60 Hz, and beyond 0.8 s for vibration in the range 60-200 Hz, there may be no further increases in sensation. These durations might then be used as "time constants" for the evaluation of response.

7.6 Vibration discomfort

Exposure to vibration can cause health problems and discomfort to the human body. Studies have confirmed that the human body is affected by whole-body vibration with respect to five different physical and psycho-physical phenomena which are: comfort [32], motion sickness [33], interference with performance [6], perception of vibration [34] and destruction of health [35].

There is ample evidence accumulated over the last 30 years, both in animal and human studies that prolonged exposure to vibration can result in bodily damage. Vibration induced injury has been documented in multiple systems, including: the spine causing back pain; the peripheral nervous system resulting in neuropathy, carpal tunnel syndrome, tingling in fingers and/or white finger syndrome; the digestive system; female reproductive system; and the vascular and vestibular systems.

Several reviews have shown an association between exposure to seated whole-body vibration and low back pain (Bernard 1997, Bovenzi & Hulshof 1998, Lings & Leboeuf-Yde 2000). However, no dose-response relationship has been established. Therefore, the general opinion is now that occupations with exposure to whole-body vibration are at risk for development of low back pain, rather than pointing out whole-body vibration as the single causal factor [5]. Today, the knowledge base is considered insufficient to suggest an association between exposure to whole-body vibration and neck and shoulder symptoms (Wikström et al 1994, Bernard 1997, Bovenzi & Hulshof 1998). Most epidemiological studies on health effects have focused on magnitudes in the vertical direction and knowledge about health effects due to exposure to whole-body vibration in horizontal directions is sparse. Furthermore, most knowledge on the relation between whole-body vibration exposure and health outcome are based on studies that are of cross-sectional or case-control type. These types of studies have a lower validity compared to prospective cohort studies.

Work machine operators have in general more health problems with back and neck than a reference group, which is not daily exposed to vibration [1].

In general, workers can be affected by blurred vision, loss of balance, loss of concentration etc. In some cases, certain frequencies and levels of vibration can permanently damage internal body organs. Worker exposure to high levels of vibration from powered hand tools can cause vibration syndrome symptoms such as numbness, pain, tingling and blanching. Vibration syndrome exposures induce adverse circulatory and neural effects in the fingers and hands that can become irreversible if left unchecked over as little as one year's time. Reduced tactile feeling and dexterity resulting from these exposures decreases workers' ability to perform critical tasks with precision. Often called vibration white finger disease (VWF), this condition is progressive and debilitating. Pneumatic and electric powered hand tools are often the cause of these unacceptable exposure levels, and even hand tools that were initially selected to emit lower levels of vibration may degrade through typical use and lack of (or improper) maintenance, leading to increasing and ultimately unacceptable levels over the working life of the tool.

The first published international recommendation concerned with vibration and the human body is ISO 2631-1978 which sets out limitation curves for exposure times from 1 minute to 12 hours over the frequency range in which the human body has been found to be most sensitive, namely 1 Hz to 80 Hz.

Table 5 gives an indication of typical human perception of vibration.

Table 5 Vibration and human perception of motion [2]

Approximate vibration level (mm/s)	**Degree of perception**
0.10	Not felt
0.15	Threshold of perception
0.35	Barely noticeable
1.0	Noticeable
2.2	Easily noticeable
6.0	Strongly noticeable

Note: The approximate vibrations (in floor of buildings) are for vibration having frequency content in the range of 8 Hz to 80 Hz.

It is apparent that discomfort is related to the vibration frequency [6]. A constant magnitude does not produce the same discomfort at all vibration frequencies. At low frequencies, where the body response as a virtually rigid system, discomfort will tend to be proportional to acceleration. The extent of the region of maximum response will depend on whether there is one major resonance (as with lateral seat motion) or several (as with vertical seat motion).

Some of the whole-body vibration effects may not result in injury or health damage but can cause problems with performing different tasks. They may affect (BS 6841: 1987) the senses, and create problems with collecting problems. Moreover they may affect the level of stimulation, motivation or fatigue and the intentional actions. Some of the effects can be frequency related as certain parts of the body are in resonance with the vibration received. Vision, for instance, is mainly affected by vibration at frequencies between 20 to 90 Hz. Posture is another example of effects related to frequency, because people subjected to vibration in frequency range from 1-30 Hz experience difficulties in maintaining a correct posture and experience an increased postural swing.

It has been shown [28] that changes in posture can significantly alter the transmission of vibration to the body and it is obvious that such changes can alter vibration discomfort. Vibration magnitudes in excess of about 3 ms^{-2} r.m.s. can be very uncomfortable and subjects would be very likely to attempt to improve the sensations they cause. At high frequencies, small postural changes can greatly reduce the transmission of vibration to the body, whereas at low frequencies posture has less effect. Furthermore, it has been shown that there are non-linearities in the dynamic response of the body which tends to become "softer" with higher magnitudes of vibration.

Some effects are not directly frequency dependent or maybe difficult to associate with specific frequencies, but are related to the cumulative effects of exposure over a range of frequencies. In general they cause imbalance, disorientation and lack of co-ordination, which then leads to stress, fatigue, interference with instrument readings, operation of tools etc. They can also result in impaired reflex action, distraction and annoyance.

Some adverse effects are due to the combination of vibration with other physical factors like noise, temperature, non-ergonomic design of equipment, protective clothing etc that are common at workplaces. This combination can also cause stress, fatigue and problems with employee task performance.

Prolonged exposure to vibration can cause also digestive system diseases. Often observed in persons exposed to whole-body vibration over a long period of time. Associated with the resonance movement of the stomach at frequencies between 4 and 5 Hz. In addition, prolonged exposure to whole-body vibration at frequencies below 20 Hz can cause problems to cardiovascular system. For example, hyperventilation, increased heart rate, oxygen intake, pulmonary ventilation and respiratory rate.

A review in the *Handbook of Human Vibration* [6], upon which these comments are based, provides considerably more detail on this topic.

7.7 Beneficial effects of vibration

Vibration has been studied extensively in order to evaluate eventual dangerous effects on humans at specific amplitudes and frequencies. On the other hand, recent work has suggested that low amplitude, low frequency mechanical stimulation of the human body is a safe and effective way to exercise musculoskeletal structures. In fact, there have been reported [9-15] increases in muscular strength and power in humans exercising with specially designed exercise equipment (specially designed vibrating plates producing sinusoidal vibrations).

The body depend on a range of structures and mechanisms to regulate the transmission of impact shocks and vibrations through the body including: bone, cartilage, synovial fluids, soft tissues, joint kinematics, and muscular activity. Changes in joint kinematics and muscle activity can be controlled on a short time scale and are used by the body to change its vibration response to external forces. It has been proposed that the body has a strategy of ‘‘tuning’’ its muscle activity to reduce its soft tissue vibrations in an attempt to reduce such deleterious effects [16]. This idea would predict that the level of muscle activity used for a particular movement task is, to some degree, dependent on the interaction between the body and the externally applied vibration forces. It has been proposed that vibrations could be used as a training aid.

The possibility of using whole body vibration in an athletic setting was introduced by Russian scientists, who developed specific devices to transmit vibratory waves from distal to proximal links of muscle groups, mainly during the performance of isometric exercises [17]. Whole-body vibration training has been shown to cause clear metabolic responses similar to other forms of exercise. Rittweger [18] studied whole-body vibration training to exhaustion with an extra weight. Results showed an O_2 uptake of less than 50% of VO_2max.

An acute reduction in vertical jump was observed, suggesting that vibration exercise to fatigue can impair neuromuscular performance. The early impairment of muscle performance was shown to be recovered 20 seconds after the end of the fatiguing vibratory exercise. Kerschan-Schindl [19] confirmed a significant increase in muscle blood volume in the calf and thigh and a significant increase in mean blood flow velocity in the popliteal artery after vibration exercise on a vibrating plate (26 Hz, 3 mm amplitude). The above studies seem to indicate that whole-body vibration training may represent a mild form of exercise for the cardiovascular system [18, 19, 20]. Furthermore, because of its reported beneficial effects in reducing low back pain [21], pain sensation, and pain related limitation, it may be a viable alternative for a patient who cannot run and/or lift weights. However, the extensive literature on the dangerous effects of whole-body vibration on the spine suggests that more, well controlled, long term intervention studies are needed before whole-body vibration training can be prescribed for patients with low back pain.

Cardinale and Wakeling [22] considered the effects of vibration on neuromuscular performance. Ten days of whole-body vibration (26 Hz, 10 mm, total exposure time 100 minutes) resulted in an increase in average jumping height and power output during repeated hopping in active subjects. Bosco observed changes in neuromuscular performance and plasma hormone levels in 14 young, athletic individuals following whole-body vibration [10]. When whole-body vibration training is performed with small amplitudes for a short time by physically active people, it is unlikely to produce significant improvements in force and power generating capacity of the lower limbs. However, when resistance exercise is performed on a vibrating plate, it seems that even physically active people can improve vertical jumping ability more than by resistance exercise alone [23].

Vibration loading may have potential for preventing and treating osteoporosis across a direct, vertical stimulus to the skeletal structure of the user, consequently directly stimulating the cells responsible for producing a higher bone mineral density. As a result, whole-body vibration could become the non-invasive, mechanically mediated intervention for osteoporosis. It could be a non-pharmacologic approach, based on stimulating bone-physiology as a means of inhibiting the decline in bone mineral density that follows menopause.

Russian scientists used the whole-body vibration for many years to rehabilitate their cosmonauts after returning from space to help restore atrophied muscles and bone density compromised due to the weightless environment of space. NASA-funded scientists suggest that astronauts might prevent bone loss by standing on a lightly vibrating plate for 10 to 20 minutes each day.

The whole-body vibration training may be an effective exercise intervention for reducing the results of the ageing process in musculoskeletal structures. It would also appear that vibration may be an effective countermeasure to microgravity and disuse. It is though important to identify the characteristics of harmful vibration and this can be done by establishing protocols on accurate description and comparison of the outcome parameters and variables of vibration characteristics, i.e. magnitude, frequency, direction, duration and variation with time and to conduct further studies to understand the neurophysiological mechanisms involved in muscle activation with vibration in order to be able to prescribe safe and effective whole-body vibration training programmes. Not only the optimal frequency and amplitude need to be identified but also the level of muscle activation that would benefit more from vibration stimulation.

7.8 Whole-body vibration standards

This paragraph gives an overview of the existing standards and regulations for measuring and evaluating whole-body vibrations with international character mainly from the German Institute for Standardization (DIN, "Deutsches Institut für Normung e.V"), the British Standards (BS) and the International Standards Organization (ISO).

To be able to assess the effects of vibration on humans, exposure standards have been introduced. The word "standard" has many different meanings and interpretations including defined evaluation procedures, limits, indications of what individuals may expect, quality or acceptability, etc. Several existing standards on human response to vibration exhibit a confusing mixture of objectives: there has been a tendency to produce human vibration standards which partially define a vibration evaluation procedure and partially define a vibration limit. In several standards incomplete knowledge and uncertainty has been reflected in the definition of ambiguous evaluation procedures with rigid limits, rather than unambiguous evaluation procedures with uncertain limits.

"Since a limit is meaningless without the evaluation procedure, it is clear that a standardization of procedures is a prerequisite to the standardized limits" (Griffin, 1990). When the two possible principle functions of standards are separated in this way it also becomes clear that a standard does not even need to define limits. In addition, the human body is exposed to vibrations at varying locations which is another aspect of standards: limits, which take into account all situations worldwide, will probably not be optimal for many local areas or specific activities, for example in industry, traffic, daily life, buildings, etc.

The standardization engage the reaching of agreement between different individuals who may have different interests and capability, who may be subject to different financial, commercial, technical and political constraints, and hope to apply the standard to different problems. A standard is therefore an expression of what could be agreed by certain individuals at a particular time.

The first German standard for the evaluation of effects of vibration on human being was the VDI (Verein Deutscher Ingenieure) 2057, edited in 1963. This standard was notable in that it mentioned the problems of assessing the effects of discontinuous vibration but did not indicate how shock motions should be assessed.

The second published German standard was the DIN 4150 ("Vibrations in buildings, 1975). It was made for architects and engineers who work in the building trade. This standard is based on the VDI 2057 and on some other standards from the building trade. In addition, the VDI 2057 takes into account that vibrating surfaces emit sound (infrasound and audible sound).

The ISO 2631 was published in 1974 for the evaluation of motion in transport and near industrial machinery. It gives numerical values for limits of exposure to vibrations transmitted from solid surfaces, e.g., in buildings to the human body in a frequency range from 1 to 80 Hz. In the last nearly 30 years the basic standard has been undergoing complete revision so as to eliminate remaining ambiguity, to remove or replace those aspects of the document which have been found to be either untenable or unnecessary, and to provide additional guidance where the standard is known to be insufficient. The last revisions are: from 1997 for the Part 1 and from 1989 for the Part 2 whereas the committee started with a new revision in the year 2000 for Part 2.

The ISO 2631 defines methods for quantification, evaluation and analysis on human response to whole-body vibrations concerning different aspects such as the health risk, the comfort and perception and the motion sickness. ISO 2631-1 (1974) gives an overview of the used symbols and subscripts, vibration axes, frequencies and magnitudes. Defines also measuring methods and analysis parameters which depend on the time and frequency domain, psychophysically motivated weighting functions, etc. ISO 2631-1 defines how to measure vibration and evaluate its significant but it doesn't include vibration exposure limits.

ISO 2631-1 (1997) distinguishes three main human criteria which can be used to assess vibration and its effect on humans in different situations. They are:

- Health: effects of periodic, random and transient vibration on the health of persons exposed to whole-body vibration during travel, at work or during leisure activities.
- Comfort and perception: estimation of the effect of vibration on the comfort of persons who are exposed to whole-body vibration during travel, at work or during leisure activities; and
- Motion sickness: effects of oscillatory motion on the incidence of kinetosis (motion sickness).

ISO 2631-2 (1989) defines how the methods of the basic standards should be extended to allow the assessment of building vibrations. Limits of acceptability of vibrations in various building types and perception thresholds in all three directions (x, y, z-axes) for whole-body vibrations are also included in this part. The principal frequency weightings are based on the specified curves in the ISO 2631-1.

The British Standard 6472 (1984) was based upon a draft of ISO DIS 2631-2 and provides a guide to evaluation the human exposure to vibration in buildings in a frequency range from 1 to 80 Hz. This standard used a similar table of basic multiplying factors with only one change, the multiplying factor for night-time shock excitation in residences is set at 20.0.

Many additional standards are available and some of these promote the standardization of the definition of terms, specify relevant test procedures, or give requirements for the reporting of information. Some of the international standards are listed in Appendix A.

More studies are still required to attain a meaningful dose-response relationship between the amount of vibration entering the body and clinical symptoms so that the safe level can be established and vibration eliminated as an occupational health hazard.

References – Chapter 7

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CHAPTER 8

Mechanical model of the human body

The study of the response of the human body to vibration is an important part of biomechanics research, and experimental and numerical investigations have been conducted for many years to give information for what concern the dynamic behaviour of the human body and the interaction between the body and the structure which transmit the vibrations.

For what concern the indirect measurement of the human whole-body vibration, various biodynamic models have been developed to describe human motion from single degree of freedom to multi-degree of freedom models. These models can be divided as: lumped parameter and distributed model. The lumped parameter models consider the human body as several rigid bodies and spring-dampers. The distributed model treats the spine as a layered structure of rigid elements, representing the vertebral bodies, and deformable elements representing the intervertebral discs by the finite element method.

A one-degree-of-freedom model was suggested in a study [8] and the driving-point impedance of the human body was considered. ISO 7962 [9] describes a 4-degree-of-freedom model based on the seat-to-head transmissibility. However, this model has only one-dimensional vertical motion and the posture and input acceleration are not well defined. In another study [10], a biodynamic model was developed using the simulation responses of the model subjected to pure sinusoidal vertical vibration. Human computer models can be developed to predict the vibration frequencies of the human body for a particular posture and for particular conditions. In addition, they can estimate the joint and muscle forces during the human exposure to whole-body vibration. In a study [11] was developed a finite element method model and was executed modal analysis to verify the natural frequency of each segment and showed the mode of the principal resonance at about 5 Hz and the second resonance at about 8 Hz. It was also showed that a change of posture from erect to slouched decreased the natural frequency of human body. Wei and Griffin [12] determined the biodynamic model parameters using the apparent mass of the hip. Mansfield and Lundstrom [13] developed models with parallel three-degree-of-freedom systems to represent apparent mass of the seated body exposed to horizontal vibration. In another study [14], two models were developed having 4 and 5 lumped mass parameters along with apparent mass and transmissibilities.

8.1 Mathematical model of applied mechanical vibrations

A viable alternative to experimental evaluation for evaluating the whole-body vibration is to approximate the human body by a mathematical model and analyse the desired behaviour of the model.

The human body can be considered as a complex organic system. As a mechanical system it contains a number of linear as well as non-linear elements, and the mechanical properties are quite different from person to person. A discrete model of the human body can be used to study the response of the human body to whole-body vibration. This model is could be realized by separating the mass, elasticity and damp properties of different body sub-systems and substitute them with mechanical elements. The magnitude of vibration and the natural frequency of the system depend on the following properties: *m* mass ($N.s^2.m^{-1}$), *k* stiffness ($N.m^{-1}$) and *c* damping ($N.s.m^{-1}$).

Muksian and Nash [17, 18] formulated nonlinear 3- and 7- degrees-of-freedom models of seated human. Greene and McMahon [19] represented a standing person by conventional spring-mass-dashpot system and determined the effective lumped stiffness and damping of the leg from the measurements of resonant frequencies of the subjects bounding on spring boards.

So, it is possible to write a force equilibrium equation for a general vibrating system as:

$$m \cdot \ddot{x} + c \cdot \dot{x} + k \cdot x = F(t) \quad (1)$$

To understand why the human body is more sensitive to some frequencies than to other, it is useful to consider the human body as a complicated visco-elastic system with many masses, spring and dampers. In Fig. 1 is shown a mechanical model of human body with the resonance vibration frequency band for each sub-system. Each sub-system has its own resonance frequency band and the interactions between sub-systems are influenced by the body's position (standing or seated position). The specific example considers the abdominal part with a resonance occurring in the 4-8 Hz ranges and the head-neck part with a resonance occurring in the range 20-30 Hz.

The natural frequency of a vibrating system depends on its stiffness and mass. Within the skeletal muscles, each cross bridge between the actin and myosin myofilaments generates some stiffness, [1, 7] and so the tissue stiffness (and therefore natural frequency) can be increased with increases in muscle activity. Indeed, studies have shown that increases in the natural frequency of whole muscle groups do concur with the joint torques developed by the muscle and typically range between 10 and 50 Hz for the lower extremity muscles (zero to maximal activity [2]). Muscles can also damp externally applied vibrations, and, indeed, more vibration energy is absorbed by activated muscle [3] than by muscles in rigor [4], suggesting that the active cross bridge cycling is an important part of the damping process. Studies have shown that the damping coefficients of whole muscle groups increase with muscle activity [3, 5], supporting the idea that the cross bridge mechanisms are important. A maximally activated muscle can damp free vibrations so that the tissue oscillations are virtually eliminated after a couple of cycles [6].

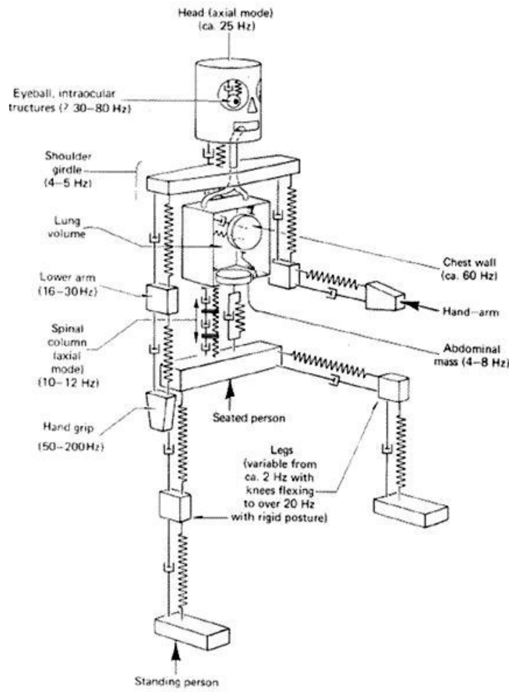

Figure 1 Simplified mechanical system representing the human body standing on a vertically vibrating platform.

A simplified lumped mass-spring-damper model of the human body was developed for this study to evaluate the vibration transmissibility and dynamic response of the human body to vertical vibrations in standing posture. The mechanical model consists in 17 masses, 18 springs and 18 dashpots. Fig. 2 displays the 17-degrees-of-freedom vibratory system.

Considering the case of free vibrations, the equations of motion of the vibratory model may be written as:

$$\{M\}\{\ddot{X}\}+\{K\}\{X\}=0 \qquad (2)$$

where $\{M\}$ and $\{K\}$ are, respectively, the mass and the stiffness matrices of order 17x17. The matrix $[M]$ is a diagonal matrix of 17 mass elements. The stiffness matrix may be easily constructed by the usual methods of vibration analysis. The natural frequencies of the model may be obtained once the mass and the stiffness matrices in Eq. 2 are available.

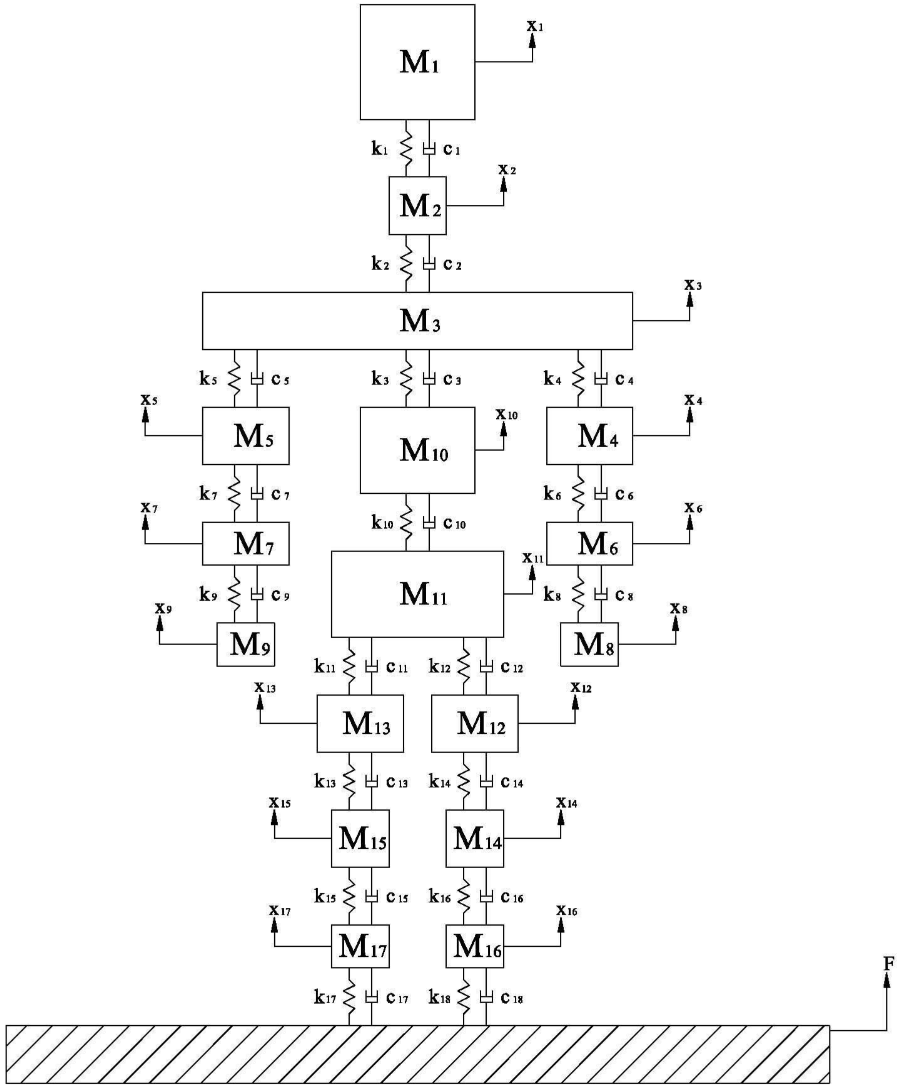

Figure 2 Mechanical model of a standing human body.

The mechanical model described above has been implemented in a Matlab 2008® environment, and several tests have been carried out. The obtained results, although not strictly related to the rest of the study, have been useful for the better understanding of the process, and could be used for a future research.

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CHAPTER 9

Vibrating table

Considering that the human body is a complex organic system, experimental investigations play an important role in studying whole body vibration. A vibrating table is often adopted in these kind of investigations.

9.1 Mechanical parameters

The vibrating tables currently available on the market deliver vibration to the whole body by means of oscillating plates using two different systems: (a) reciprocating vertical displacements on the left and right side of a fulcrum; (b) the whole plate oscillating uniformly up and down (Fig. 1).

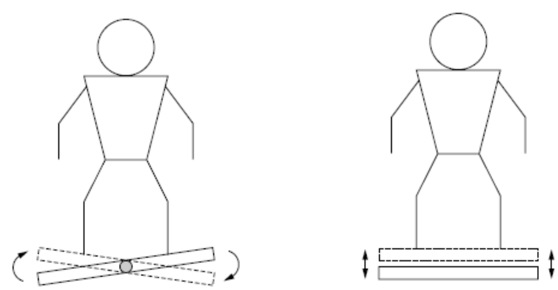

Figure 1 Two different systems of vibrating tables [1].

Whole body vibration exercise devices deliver vibrations across a range of frequencies (15–60 Hz) and displacements from < 1 mm to 10 mm [1]. The acceleration delivered can reach 15 g (where 1 g is the acceleration due to the Earth's gravitational field or 9.81 m/s^2). Considering the numerous combinations of amplitudes and frequencies possible with current technology, it is clear that there are a wide variety of whole body vibration protocols that could be used on human body.

For this study it was used the first type of vibrating table which includes the reciprocating vertical displacements on the left and right side of the table. This device delivers vibrations across a range of frequencies: 20-50 Hz. For the registration of the input motion of the device there were placed two markers, one on the left and one on the right side of the table.

The input motion from the vibrating table in terms of acceleration, with a frequency of 20, 30 and 45 Hz, is shown in the following figures.

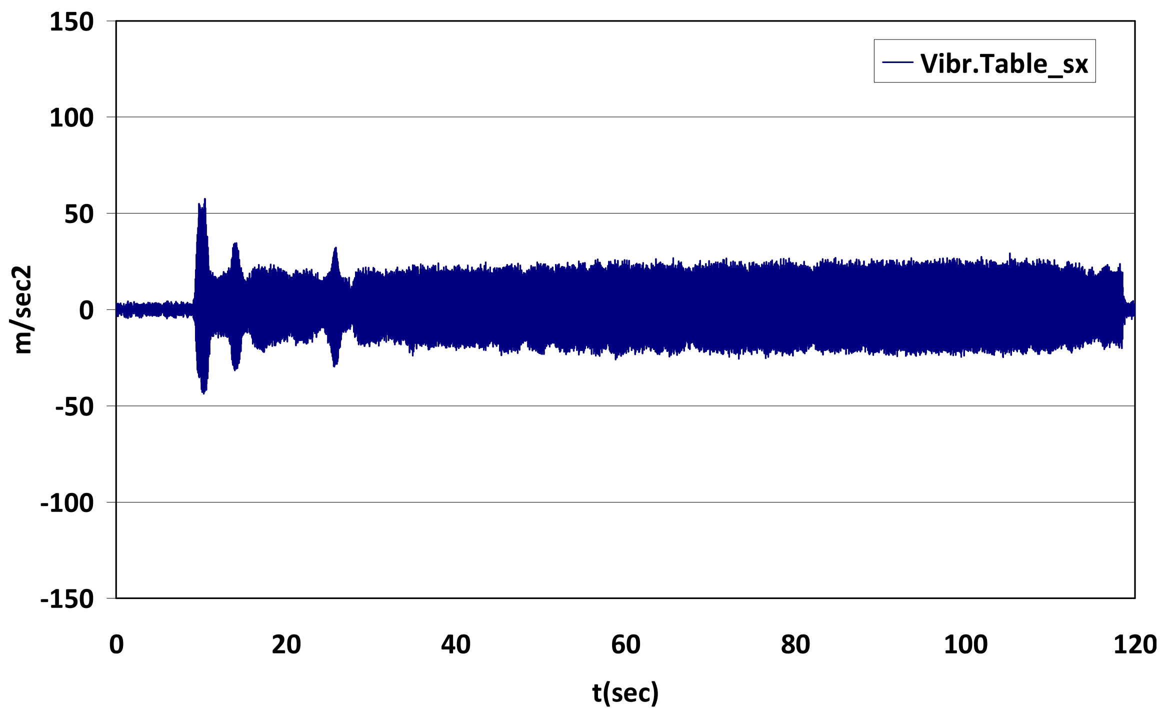

Figure 2 Acceleration time history (z-axis) of left side of the vibrating table with a frequency of 20 Hz.

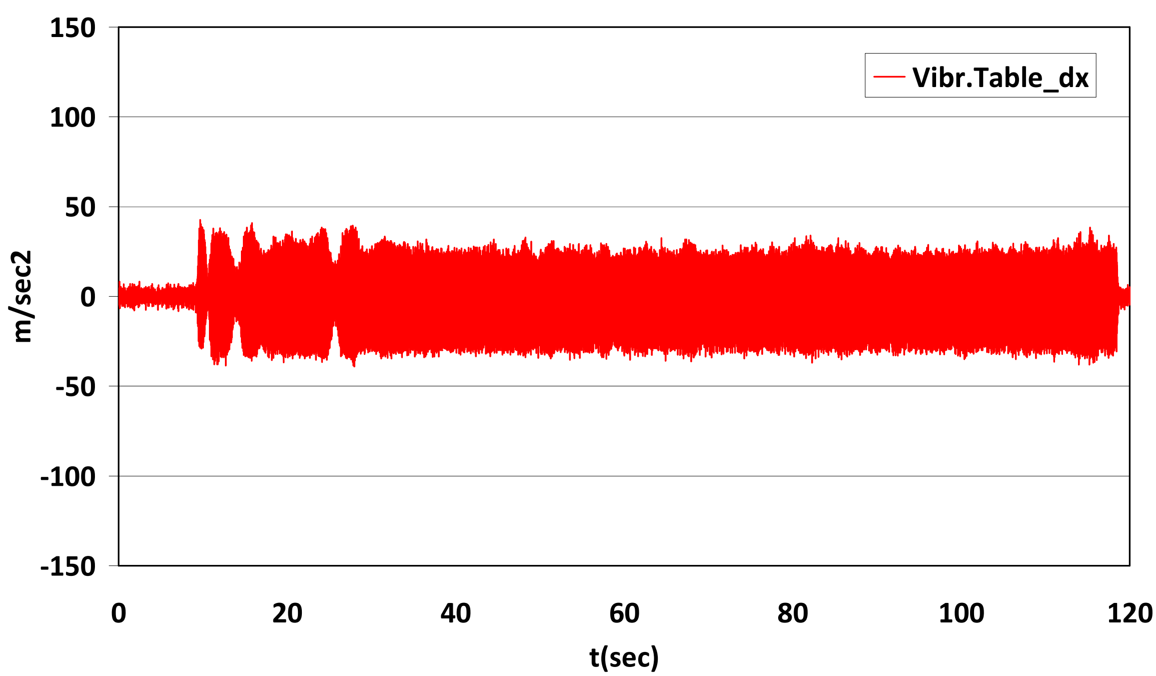

Figure 3 Acceleration time history (z-axis) of the right side of the vibrating table with a frequency of 20 Hz.

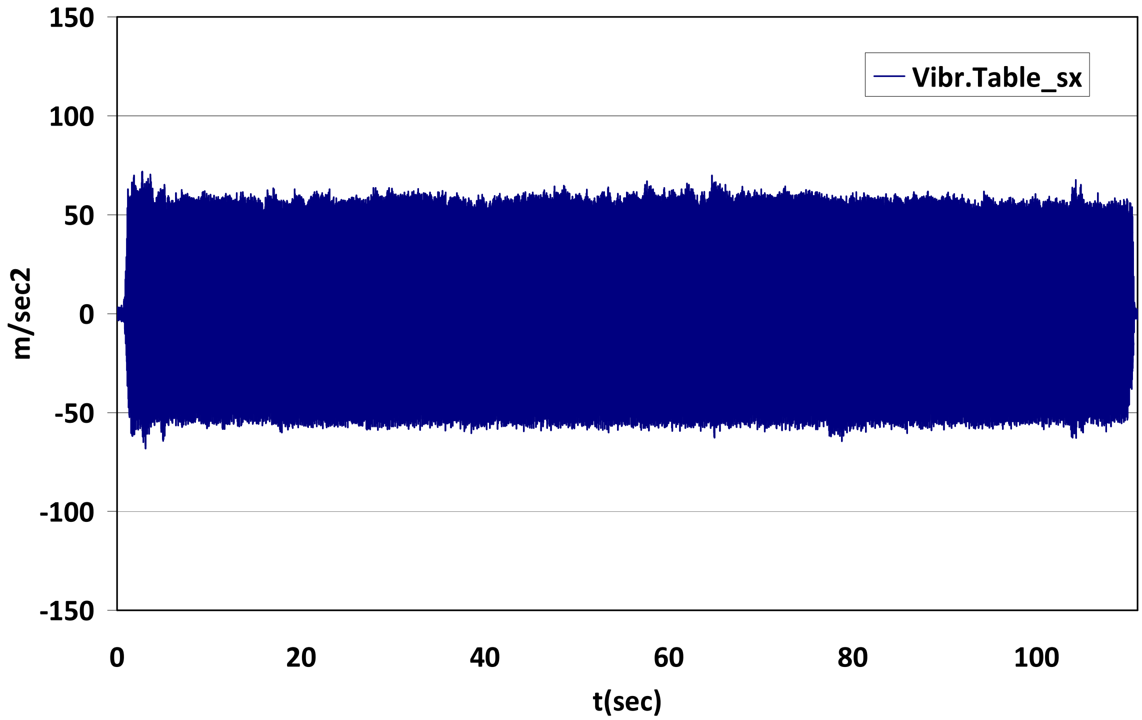

Figure 4 Acceleration time history (z-axis) of the left side of the vibrating table with a frequency of 30 Hz.

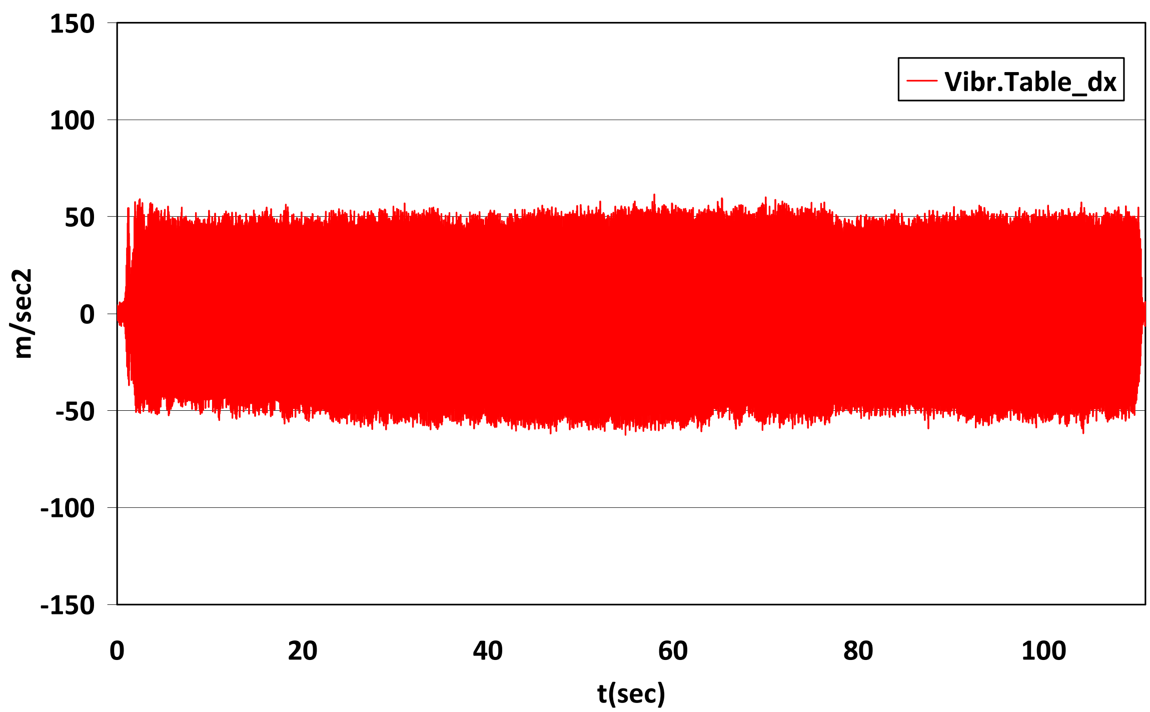

Figure 5 Acceleration time history (z-axis) of the right side of the vibrating table with a frequency of 30 Hz.

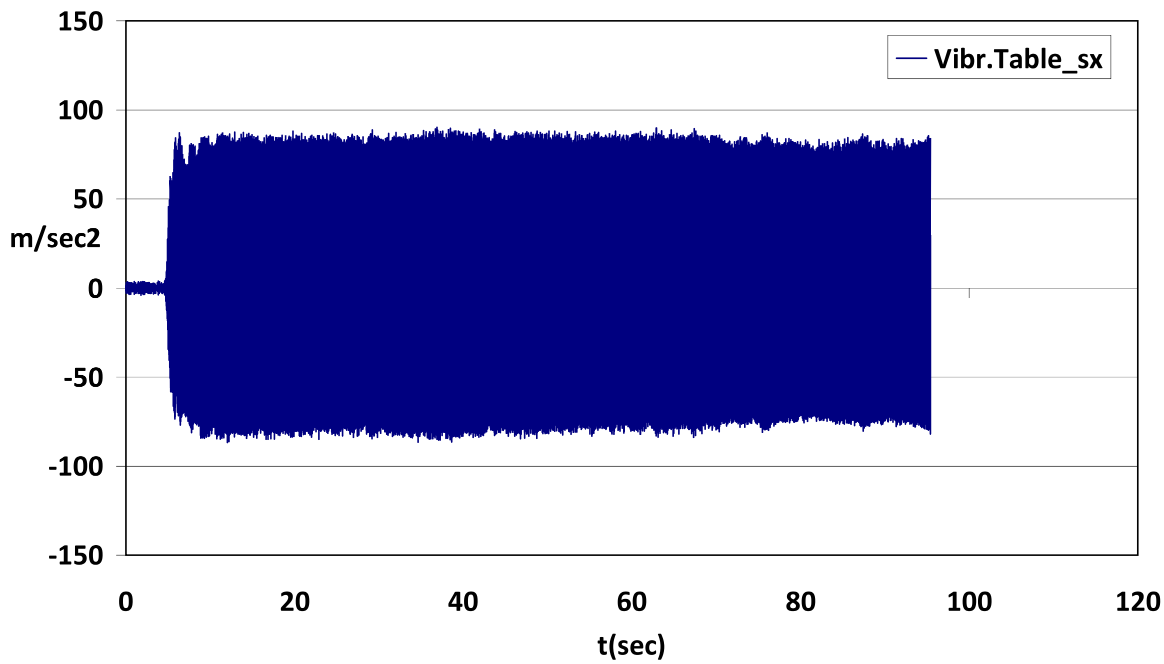

Figure 6 Acceleration time history (z-axis) of the left side of the vibrating table with a frequency of 45 Hz.

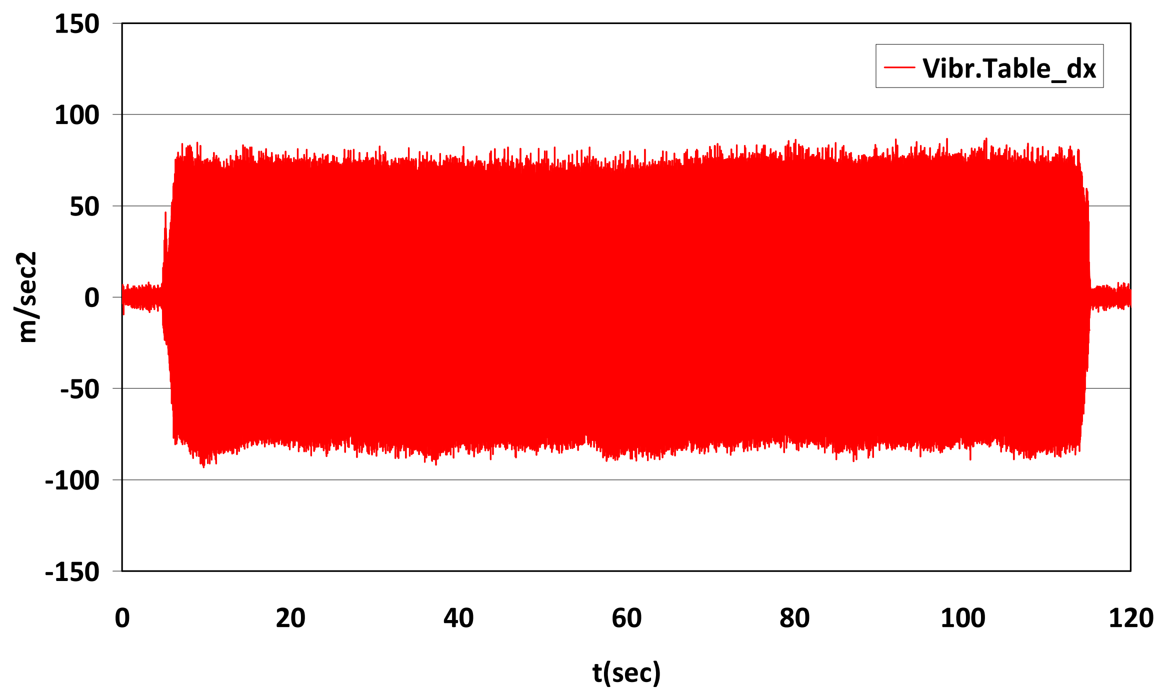

Figure 7 Acceleration time history (z-axis) of the right side of the vibrating table with a frequency of 45 Hz.

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CHAPTER 10

Data acquisition and elaboration systems

In order to understand how the standing human body responds to vertical vibrations, it is useful to address the problem with an integrated and global approach. Estimating the energy expenditure of the subject by means of the variation of the temperature with the aid of infrared thermography, the displacement of the muscles with the aid of a motion analysis system and the oxygen uptake with the aid of a telemetric system, it is possible to obtain interesting results regarding how it behaves under different vibration conditions.

In the next paragraphs, the systems used for the acquisition and elaboration of the data of this thesis are briefly described.

10.1 Vicon Motion System

In general, a Motion Capture System involves the process of recording a live motion event and translating it into usable mathematical terms by tracking a number of key points in space over time and combining them to obtain a single 3D representation of the performance. In particularly, human motion capture which is a very realistic example of a skeleton structure with many joints and degrees of freedom, includes tracking the movement of the head, torso, and limbs. Motion capture systems have many applications including anthropometry, ergonomics, gait analysis, motion of flexible geometry, etc.

In particular, the Vicon Motion System [8] is designed to track the movement of human body or other movement in a laboratory. Markers covered with reflective tape are placed on visual reference points on different parts of the human body.

The Vicon Motion System uses a series of cameras and is designed to track and reconstruct these markers in 3-dimensional space. During the process, the cameras are used to track and record the motion of the subject. This information will be then send to the workstation which is the central application of the Vicon software used to collect and process the raw 2D video data. It takes the two-dimensional data from each camera and then combines them with the camera coordinates and other cameras views to obtain three-dimensional (x, y, and z) coordinate of each marker in the list per frame in time and space. The positions calculated frame by frame are then combined to create a complete set of trajectories of the markers positions throughout the time span of the trial. This can be demonstrated by graphs showing the trajectory history of each marker in x, y, and z directions.

In an ideal situation, the reconstruction of the data from 2D to 3D should result in smooth and continuous trajectories that define the path of each marker for the duration of the trial through the capture volume. Sometimes, however, the captured data is incomplete and this happens in situations where some markers are not being seen by at least two cameras, which is the minimum requirement to calculate the position of the markers for each frame. This phenomenon is called occlusion, which results in broken trajectories, and the resulting motion will be discontinuous. In some other cases the markers are so close to each other in the view such that the calculation algorithm confuses one for another, which results in another phenomenon known as a crossover. In other cases, the software produces trajectories for markers that do not really exist in the capture space but may results from reflection of spotlight or flashing material in the motion capture space, which are known as ghost markers [9].

In this study, a Vicon MX Motion System was used for the three dimensional kinematic motion analysis with 18 reflected markers attached on the athletes body and 4 cameras.

10.2 Thermography

Thermography is a non-invasive technique that measures the temperature distribution over a surface area and converts infrared radiation emitted from the surface into electrical impulses that are visualized in colour.

Thermography dates back to the 1800s; the first 'heat picture" was produced in 1840 by the astronomer William Herschel. His thermography research began with the knowledge that sunlight was made up of all the colours of the spectrum, and that it was also a source of heat, so he set out to determine which colours were responsible for heating objects. In 1961, the first images were used in medical research to confirm that skin temperatures were elevated on the surface of the breast over a cancer. A flurry of thermography research was done in the 1970s through the early 1980s, with mixed reviews on its use. Most research was conducted on microscopically confirmed tumours and the comparison between clinical exam, mammograms and thermography in terms of their sensitivity and specificity of detecting tumours.

In thermography, the spectrum of colours indicate an increase or decrease in the amount of infrared radiation being emitted from the surface of the object.

Therefore, thermography is the determination of surface temperatures of objects and bodies with the help of infrared photography. A special-purpose camera captures what the human eye cannot see. The camera consists of an infrared-permeable lens, a transmission line and a sensitive detector. The detector converts radiation into electric signals. After processing they are transformed into pixels so that the thermogram appears on the screen (Fig. 1).

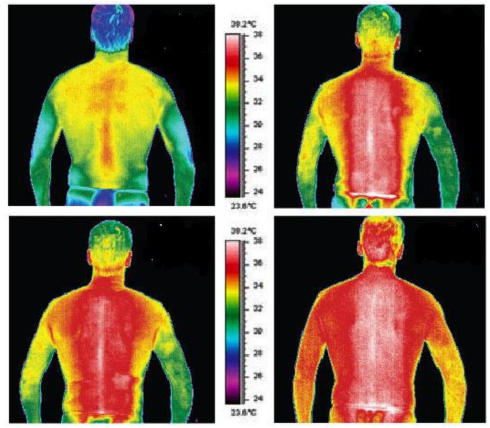

Figure 1 Thermal image of a human body.

Several studies have been performed that describe experimental requirements for thermographic studies; such as a draft free room, participant equilibrium with the room temperature for at least 20 minutes prior to assessments, and pre examination screening to reduce image abnormalities due to skin surface variations [1-6].

10.2.1 The Infrared Camera System

The basic elements of an Infrared System are: a thermal excitation source; a target; a radiometer (IR camera); a signal and image analysis system (PC); and the result (display). In addition, signal degradation is omnipresent at all stages.

If a thermal gradient between the scene and the object of interest exist, the target can be inspected using the passive approach. However, when the object or feature of interest is in equilibrium with the rest of the scene, it is possible to create a thermal contrast on the surface using a thermal source , this is known as the active approach in IT. Thermal excitation introduces heat noise, i.e. non-uniformities dues to imperfect heating. This is a well-known problem in active thermography.

The target is the specimen or the scene of interest. It can be for example a subsurface flaw on a specimen or a gas leak in a complex scene. Regardless of whether the active or passive approach is used, IR signatures are weak when compared with other forms of radiation. The IR radiation measured by the radiometer results from the contribution of three different sources: the thermal energy emitted from the object; the energy reflected from the background; and the energy transferred through the material. Additionally, the atmosphere attenuates the oncoming thermal signatures.

A radiometer (IR camera) captures the (weak and noisy) thermal signatures coming from the target. The principal components of a radiometer are: the optical receiver, the detector or detector matrix, and in some cases a cooling system. Here again, every element of the radiometer contributes to further degrade the signal, i.e. optical, electronic and electromagnetic noise. As a result, a data processing step is generally required.

The resulting IR Imaging Systems usually operate in two high transmissivity atmosphere windows: *LWIR* (8-14 μm) and *MWIR* (3-5 μm). It can be seen from Wien's Law that high temperature bodies have their peak emission at short wavelengths, while objects emitting at ambient temperature have their maximum emission at longer wavelength bands. Therefore, the MWIR band is preferred when inspecting high temperature objects and the LWIR band when working with near room temperature objects. Other important criteria for band selection are: the operating distance, indoor-outdoor operation, temperature and emissivity of the bodies of interest. For instance, long wavelengths (LWIR) are preferred for outdoor operation since they are less affected by radiation from the sun. LWIR cameras are typically uncooled systems using a microbolometer Focal Plane Arrays commonly used in industrial IR applications, although cooled LWIR cameras using Mercury Cadmium Tellurium (MCT) detectors exists as well. On the contrary, the majority of the MWIR cameras require cooling, using either liquid nitrogen or a Stirling cycle cooler. Cooling to approximately -196^{o}C, offer excellent thermal resolution, but it might restrict the span of applications to controlled environments.

In the following paragraphs a description of the thermal imaging apparatus is given.

· **Detectors**

An infrared detector or sensor is a device that converts radiant energy into some other measurable form, e.g. an electrical current. There are two classes of infrared sensors: thermal and photonic (or quantum) detectors. A thermal detector responds to incident radiation by raising its temperature. When a thermal detector is at equilibrium there is no thermal conduction, the sensor simply radiates energy at the same rate as it absorbs it. The detector's temperature will increase whenever the incident radiation rises above the equilibrium state, the detector absorbs more energy than it radiates. The excess temperature is then removed away by conduction.

Types of thermal detectors include thermocouples, bolometers, pneumatic detectors, pyroelectric detectors and liquid crystals.

· **Focal Plane Arrays**

Focal plane arrays (FPA) are detectors which consist of a linear or two-dimensional matrix of individual elements. They are used at the focus of imaging systems. There are two basic types of focal plane arrays: linear and area. Linear focal plane arrays consist of a single line of pixels. Area focal plane arrays consist of rows and columns of pixels.

The fill factor is an important parameter in selecting FPAs, it provides the IR-sensitive material to total surface (including the signal transmission paths) ratio. The higher the fill factor, the higher the sensitivity, the cooling efficiency and the overall image quality of the system.

· **Representing IR Images**

A common approach to represent Infrared Thermography is to display a two-dimensional (2D) map, where each element gives the intensity (e.g. temperature, time, amplitude, phase, etc.) of a point on the specimen's surface (or scene).

· **Signal Degradation**

IR signals can be affected by numerous sources of noise that contribute to degrade the signal even further. First, there is the electronic noise from the IR detector, which can be of three kinds: shot noise, caused by the random variation of the incident radiation; thermal (or Johnson) noise, resulting from the random motion of electrons in resistive materials; and flicker (or 1/f) noise, which depends on the observation frequency as 1/fn (where n is typically between 0.9 and 1.35).

Noise can also be optical, resulting from the random fluctuations of the incident radiation; heating, because of nonuniform thermal excitation and spurious reflections; environmental, electromagnetic interference induced by power lines, radio and TV broadcast, and by heavy machinery; and structural, random variability of thermophysical properties.

10.2.2 Active and Passive Thermography

There are two basic types of thermography: passive and active thermography.

Active thermography involves heating the surface of the object rapidly using an external heat source and observing how the temperature decays with time. In passive thermography there is no application of an external heating source, the camera is simply pointed at the test piece and from the thermal image a temperature map is constructed. What separates active from passive thermography is the intentional application of heating, chilling or stress (active) that results in a temperature rise or fall in a target, as compared to an otherwise in situ (passive) target.

There are basically four techniques widely used in active thermography, that differ from each other mainly in the way data is acquired and/or processed: Pulsed Thermography, Lock-in Thermography, Step-Heating Thermography and Vibrothermography.

· **Pulsed Thermography**

Pulsed Thermography is an active thermography technique for the assessment of composite materials. It is a high-speed, portable, non-contact and large area inspection technique.

Fig. 2 shows the principle of Pulsed Thermography. The surface to be inspected is heated by one or more intense light source(s) (~1kw) for periods of 1-25ms. Heat flow into the sample is altered by the presence of any subsurface flaws (disbonds, voids or inclusions), creating a temperature variation at the surface, which changes with time. These changes are recorded by the infrared camera system, which collects images at a frame rate of up to 60Hz.

A thermal map of the surface or thermogram is recorded at regular time intervals. A 3D matrix is formed (see Fig. 3) where x and y coordinates are the horizontal and vertical pixel positions respectively, and the z-coordinate corresponds to the time evolution, in which the thermograms are separated Δt *s* from each other.

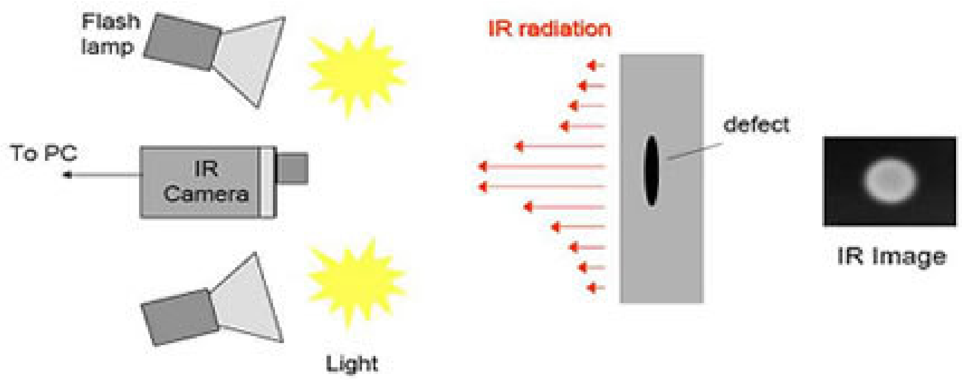

Figure 2 Principle of Pulsed Thermography.

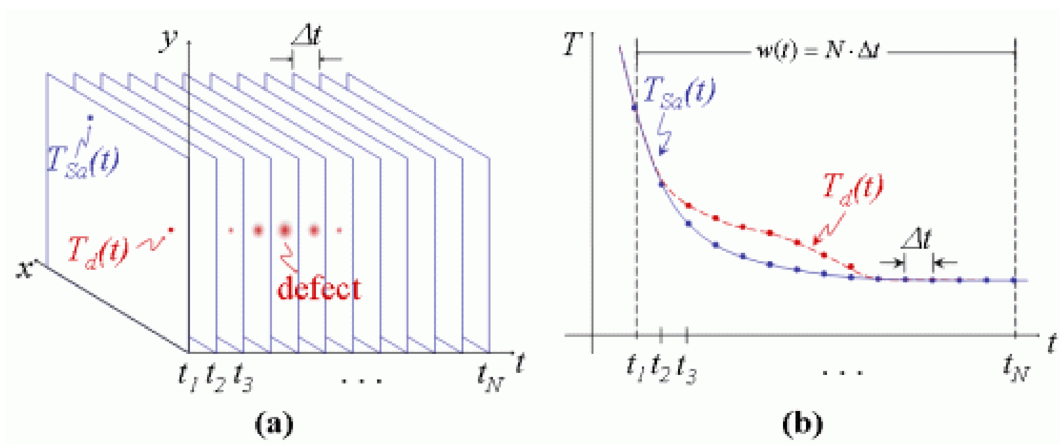

Figure 3 Temperature evolution of pulsed thermography: (a) acquisition data as a 3D matrix of images, and (b) temperature profile for a defective (dotted line) and non-defective (continuous line) pixels.

· **Lock-in Thermography**

In lock-in thermography (LT) the specimen is stimulated with a periodic energy source. Typically, sinusoidal waves are used, although it is possible to use other periodic waveforms. Internal defects, acting as barriers for heat propagation, produce changes in amplitude and phase delay of the response signal at the surface (Fig. 4). Different techniques have been developed to extract the amplitude and phase information. Fourier analysis is the preferred processing technique since it provides single images, ampligrams or phasegrams (the weighted average of all the images in a sequence). The resulting Signal-to-Noise Ratio (SNR) is therefore very high.

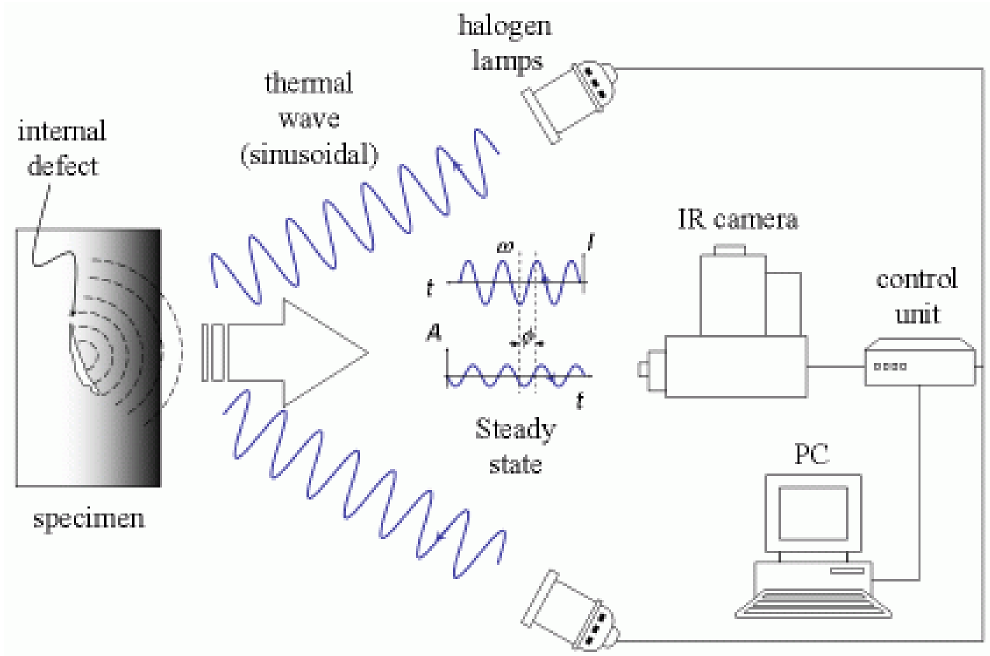

Figure 4 Experimental set-up example of lock-in thermography in reflection with optical excitation.

· **Step-Heating Thermography**

Step heating uses a larger pulse (from several seconds to a few minutes). The temperature decay is of interest; in this case, the increase of surface temperature is monitored during the application of a step heating pulse. Variations of surface temperature with time are related to specimen features as in PT. This technique is sometimes referred to as time-resolved infrared radiometry (TRIR). TRIR finds many applications such as evaluation of coating thickness – including multilayered coatings, determination of coating-substrate bond integrity or evaluation of composite structures.

· **Vibrothermography**

In the case of vibrothermography (VT), the energy is applied into the specimen by means of mechanical oscillations using, for example, a sonic or ultrasonic transducer that is in contact with the specimen (usually a coupling media is employed); see Fig. 5. In this case, the defects are stimulated internally; the mechanical oscillations transmitted into the specimen spread in all directions inside it. The mechanical energy is dissipated at the discontinuities in the form of heat waves that travel to the surface by conduction.

The technique known as vibrothermography is typically used in the inspection of cracks and micro-cracks in metallic structures, which are very difficult to inspect with optical excitation.

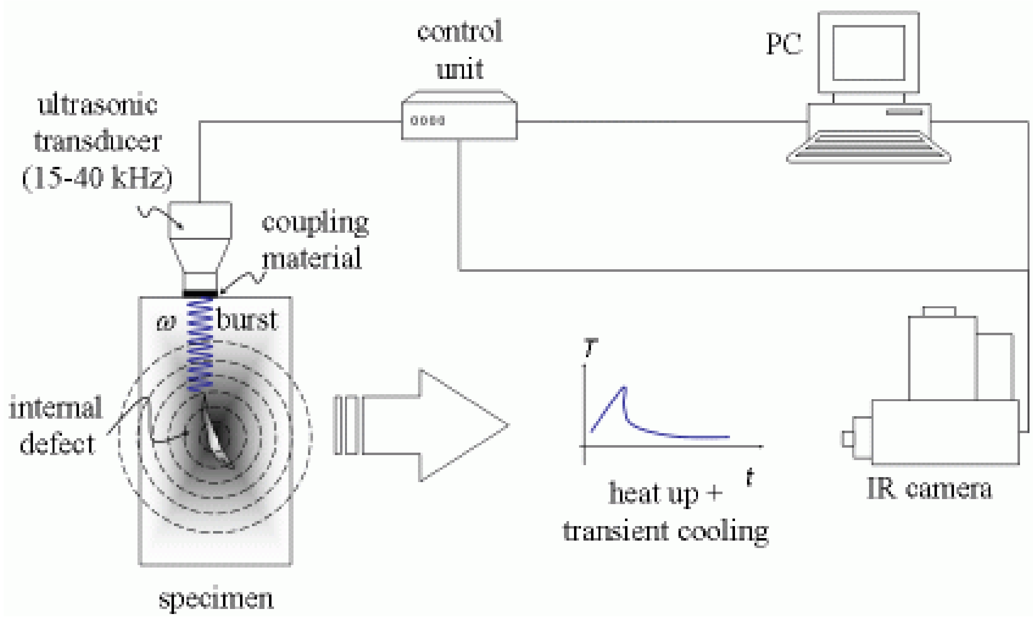

Figure 5 Experimental setup for vibrothermography inspection by Reflection in burst (pulsed) mode.

Vibrothermography is suitable for relatively small objects and it is the most appropriate technique to inspect some types of defects, e.g. micro cracks. On the contrary, it does not perform very well in some other cases in which application of optical techniques are straightforward, e.g. water detection.

10.2.3 Image Processing and Analysis

Image processing is a form of signal processing for which the input is an image, such as photographs or frames of video. The output of image processing can be either an image or a set of characteristics or parameters related to the image. Most image processing techniques involve treating the image as a two-dimensional signal and applying standard signal-processing techniques to it.

An image defined in the "real world" is considered to be a function of two real variables, for example, $a(x,y)$ with a as the amplitude (e.g. brightness) of the image at the real coordinate position (x,y). An image may be considered to contain sub-images sometimes referred to as regions-of-interest, ROIs, or simply regions.

Image processing generally can be dissected into three main areas: Encoding, Transformation and Analysis.

Encoding describes the methods by which an image can be represented as a series of binary digits. They say that an image is worth a thousand words and in terms of storage space that can be a conservative estimate. Encoding concentrates on reducing the size of the data that represents an image, for transmission or storage.

Transformation is the process of altering the image to make it more suitable for the intended purpose. Many people use software programs to remove noise and correct light imbalances in their digital photos. Operations like these can also be performed in an automated environment to prepare an image for presentation or further analysis.

Analysis allows conclusions to be drawn from an image. Image analysis can take the form of identification of features, statistical analysis, classification, measurement or a combination of these. The methods used to analyse images vary greatly.

Image processing usually refers to digital image processing, but optical and analog image processing are also possible. The term analog refers to a signal that has a continuously varying pattern of intensity. The term digital means that the data takes on discrete values. Although digital image processing, is, by far, the most important one, analogue optical image processing, including in real time, have also a major role. For instance, the implementation of Fourier processing techniques in the frequency domain gives excellent results, especially in the study of dynamic or transient processes. Furthermore, the concept of image as bidimensional entity can be easily generalized to 3D or even multidimensional image like structures processed with essentially the same tools as the conventional 2D images.

Digital image processing is a subset of the electronic domain wherein the image is converted to an array of small integers, called pixels, representing a physical quantity such as scene radiance, stored in a digital memory, and processed by computer or other digital hardware. Here, digital image processing means algorithmic recognition or analysis, enhancement and manipulation of the digital image data. Every image processing technique or algorithm takes an input, an image or a sequence of images, and produces an output.

Image processing techniques are usually divided in two major categories: radiometric and geometrical. In geometric operations in opposition to radiometric ones, the grey (colour, or any other entity in general) level in each point (pixel) of the image is changed accordingly to the image' grey values on its neighbourhood. Eventually the new grey level in one pixel can even be totally independent of its original value, for instance in edge detection. Radiometric operators act on the original images changing its brightness (colour) distribution. In digital image processing the image is represented by a 2D matrix that is processed typically by multiplication by another matrix or series of matrix sequentially.

Images:

· Greyscale Image: The greyscale image is also known as intensity image. This kind of image represented as a matrix with each pixel assigned gray intensity level. In a (8-bit) greyscale image each picture element has an assigned intensity that ranges from 0 to 255. A grey scale image is what people normally call a black and white image, but the name emphasizes that such an image will also include many shades of grey.

· RGB (Red, Green, Blue) Image: The RGB colour model is an additive colour model in which red, green, and blue light are added together in various ways to reproduce a broad array of colours. The name of the model comes from the initials of the three additive primary colours, red, green, and blue. The main purpose of the RGB colour model is for the sensing, representation, and display of images in electronic systems, such as televisions and computers.

· Binary Image: Binary images are images whose pixels have only two possible intensities 0 or 1 Binary images contains only two colours, black[0] and white[1]. The binary image requires significantly smaller memory and processing requirements. A well developed algorithms are available for binary imaging. It is ideal for industrial applications which require only silhouette of objects. The binary images also reduce transmission and storage cost as well as processing time.

There are two general groups of 'images': *vector graphics* (or line art) and *bitmaps* (pixel-based or 'images'). A bitmap is constituted of rows of pixels, contraction of the words 'Picture Element'. Each pixel has a particular value which determines its appearing colour. This value is qualified by three numbers giving the decomposition of the colour in the three primary colours Red, Green and Blue. Any colour visible to human eye can be represented this way. The decomposition of a colour in the three primary colours is quantified by a number between 0 and 255.

Some of the most common *file formats* are:

GIF: an 8-bit (256 colour), non-destructively compressed bitmap format. Mostly used for web. Has several sub-standards one of which is the animated GIF.

JPEG: a very efficient destructively compressed 24 bit (16 million colours) bitmap format. Widely used, especially for web and Internet (bandwidth-limited).

TIFF: the standard 24 bit publication bitmap format. Compresses non-destructively with, for instance, Lempel-Ziv-Welch (LZW) compression.

PS: Postscript, a standard vector format. Has numerous sub-standards and can be difficult to transport across platforms and operating systems.

PSD: a dedicated Photoshop format that keeps all the information in an image including all the layers.

For what concern the analysis of thermal images, thermal image processing allows rapid extraction of digital temperature information. Image processing is required for an accurate thermogram interpretation. Present-day systems enable the recording, storage, and processing of hundreds of digitized images at very fast rates. The thermal images are typically analyzed for the presence of hot spots which may indicate the existence of subsurface defects. Noise of multiple nature and optical distortions produce difficulties for the interpretation of the recorded data.

10.3 Physiological Data: Portable system Cosmed K4

The measurement of oxygen uptake during various physical activities is of great interest for the estimation of the energy expenditure of the human body. Portable oxygen uptake devices have been used in many studies to estimate the energy cost of the human subject during physical activities [12-15]. Either the Douglas bag method or the flow-through system is commonly used in such measurements.

In general, a telemetric system is an electrical device designed to measure VO_2 and VCO_2 in the laboratory or in the field [10]. This system has been conceived to be used as an auxiliary instrument in order to formulate lung pathology diagnosis, to perform studies concerning human physiology and to give information in sport medicine.

For this study, a telemetric system named Cosmed K4 was used for the measurement of the oxygen uptake.

References – Chapter 10

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CHAPTER 11

Pre Analysis: Finding a protocol

The aim of this study was to determine and quantify the effects of whole-body vibration to the human body in terms of energy expenditure. The variables of interest and the measuring method were: the superficial temperature of the human body with the aid of infrared thermography, the oxygen uptake with the aid of the Cosmed K4 telemetric system and the displacement of the muscles with the aid of the Vicon MX motion analysis system.

The establishment of an appropriate protocol which satisfies the aim of this study was the first goal of this research. For this purpose a literature review was conducted. What was found was that there is confusion to some extend about the whole-body vibration protocols. The duration and volume of vertical vibrations and the rest time differ in the literature, ranging from a single, 30 sec. whole-body vibration exposure [1] to 10 sets of vibration exposure of 60 sec., with 60 sec. rest between the vibration sets and a rest period lasting 6 min. after 5 vibration sets [2].

A number of studies have shown an increase on the performance of the subjects exposed to whole-body vibration; though, they all differ in the duration and the frequency of vibration by which these were obtained. Bosco et al. [2] used a whole-body vibration protocol consisting in 10 sets of vibration for 60 sec., with 60 sec. rest between, and a rest period of 6 min. after the fifth exposure, resulting in an improvement of the countermovement jump (CMJ) height. Torvinen et al. [3], found a 2.5% improvement in vertical jump height at 2 min. following vibration using a 4 min. whole-body vibration protocol (four 1 min. intervals with 1 min. rest). In another study of the same design [4], no improvement in performance was found, with the only difference between the studies being the vibration amplitude (4 mm [3] vs. 1 mm [4]). While some studies [3] declare that the vibration amplitude might be the most important variable relating the vibration effect with the improvement in performance, other studies state that the most important variable for the vibration effect might be the vibration frequency [5, 6].

The lack of consistency in whole-body vibration protocols in the current published studies makes comparison of study outcomes difficult and consequently, the establishment of an appropriate protocol occurs to be essential.

Therefore, a series of experiments was conducted in this study in order to examine the response of the human body to vertical vibrations, changing the duration of vertical vibration, the frequency of vertical vibration and the duration of rest period.

11.1 Experimental setup

Four subjects voluntarily participated to the experimental setup. They were subjected to vertical vibrations with an input motion from a vibrating table with a frequency ranging from 20 to 50 Hz and for an exposure time of 5 to 30 minutes. Two infrared thermography systems and a telemetric system (Cosmed K4) for the measurement of the oxygen uptake were used.

At the beginning of the experimental setup anthropometric measures (height and weight) were registered, together with the age of the subjects. Following this phase, a neutral climate (23°C) and a body temperature of the subjects around 37°C was guaranteed. After that, the subjects performed a series of test with a variation in the vibration frequency and duration, and in the duration of the rest period. Two different experiment types were performed: experiments with continuous vibrations and experiments with intermittent vibrations.

11.1.1 Continuous vibrations

The *first initial hypothesis* was that *continuous vibrations* determines significant changes in the energy expenditure of the human body. Therefore, the response of the standing human body exposed to continuous vertical vibrations was first investigated. The frequencies used were of 25 Hz and 45 Hz.

In the first series of experiments, the subjects were first evaluated in a control condition (without vibration) lasting 100 sec. on the vibrating table, in a standing position. The change in superficial temperature and the oxygen consumption were measured in this phase. Then, the subjects were exposed to continuous vertical sinusoidal whole-body vibrations in a standing position lasting 440 sec. and at a frequency of 25 Hz. During the exposure to the vibration, the oxygen uptake and the superficial temperature of the human body were estimated. After the vibrations, the subjects remained in the standing position for 440 sec and the change in superficial temperature and oxygen uptake were also measured.

In the second series of experiments, the subjects performed the same protocol. The frequency and the duration of vibration and rest period were not the same. The time of the exposure vibration was of 660 sec. and the frequency of 45 Hz. Also, the resting period before the vibration exposure lasted 180 sec. and the rest period after the vibration exposure lasted 800 sec.

A sample of the oxygen uptake of the subjects during the first and second series of experiment can be seen in the next figures (Figs. 1-2). The dashed lines indicate the start and the end of the period of exposure to vibration.

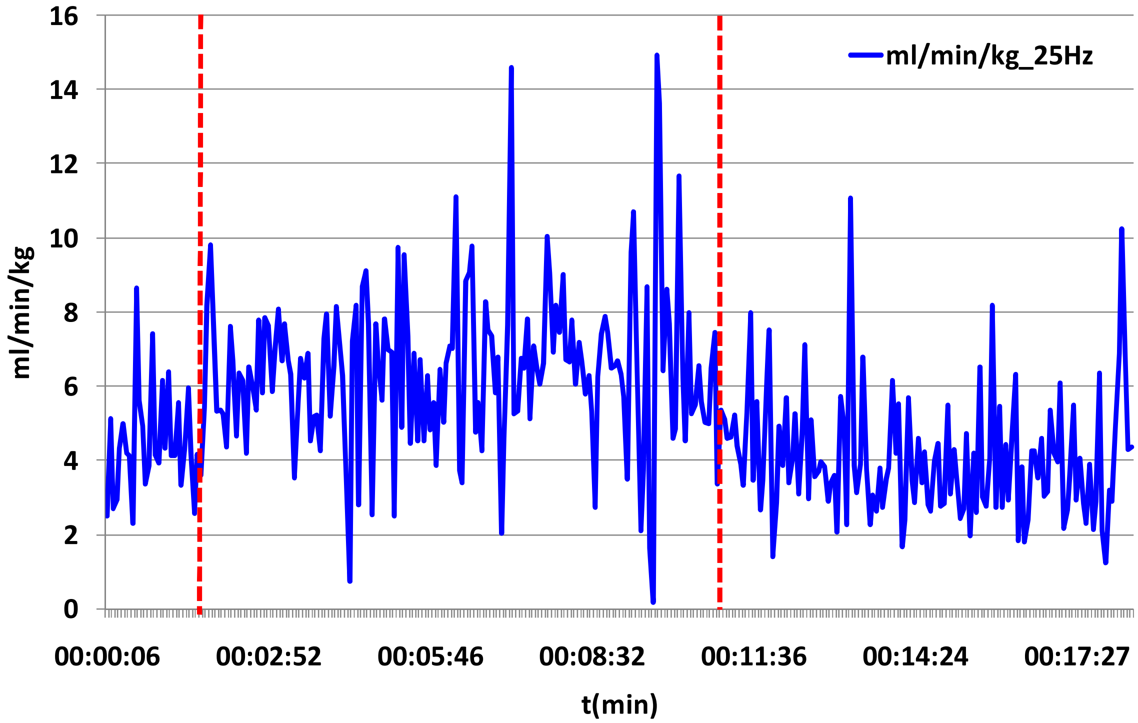

Figure 1 Oxygen uptake (ml/min/kg) of one of the subjects exposed to continuous vibration at a frequency of 25 Hz.

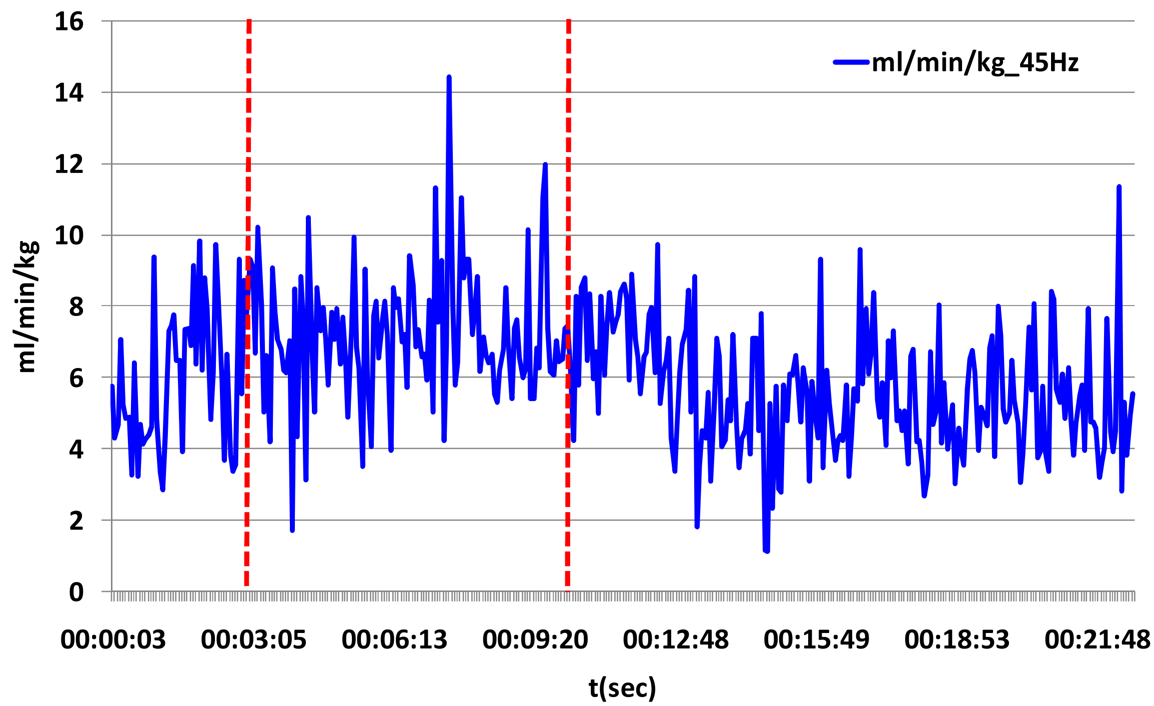

Figure 2 Oxygen uptake (ml/min/kg) of one of the subjects exposed to continuous vibration at a frequency of 45 Hz.

In Figs. 3-4 is shown the variation in the superficial temperature of the human body and in particular the variation in the superficial temperature of the head, of the abdominal and of the femur during the first and the second series of experiments.

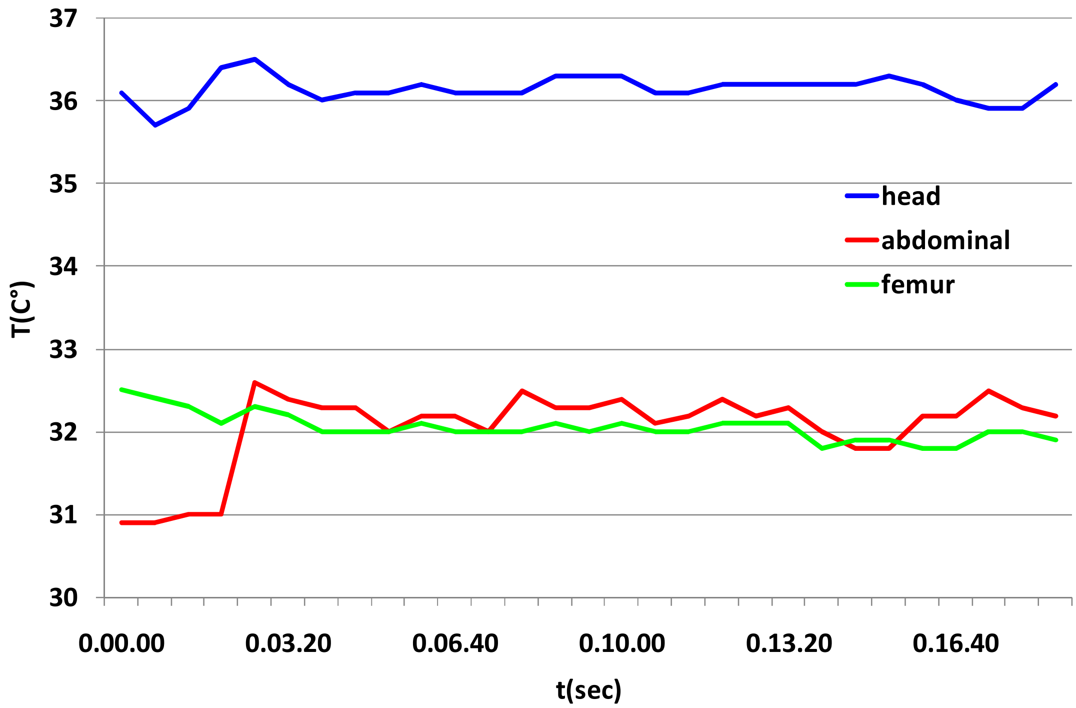

Figure 3 Superficial temperature variation of the head, the abdominal and the femur of the human body exposed to continuous vibration at a frequency of 25 Hz.

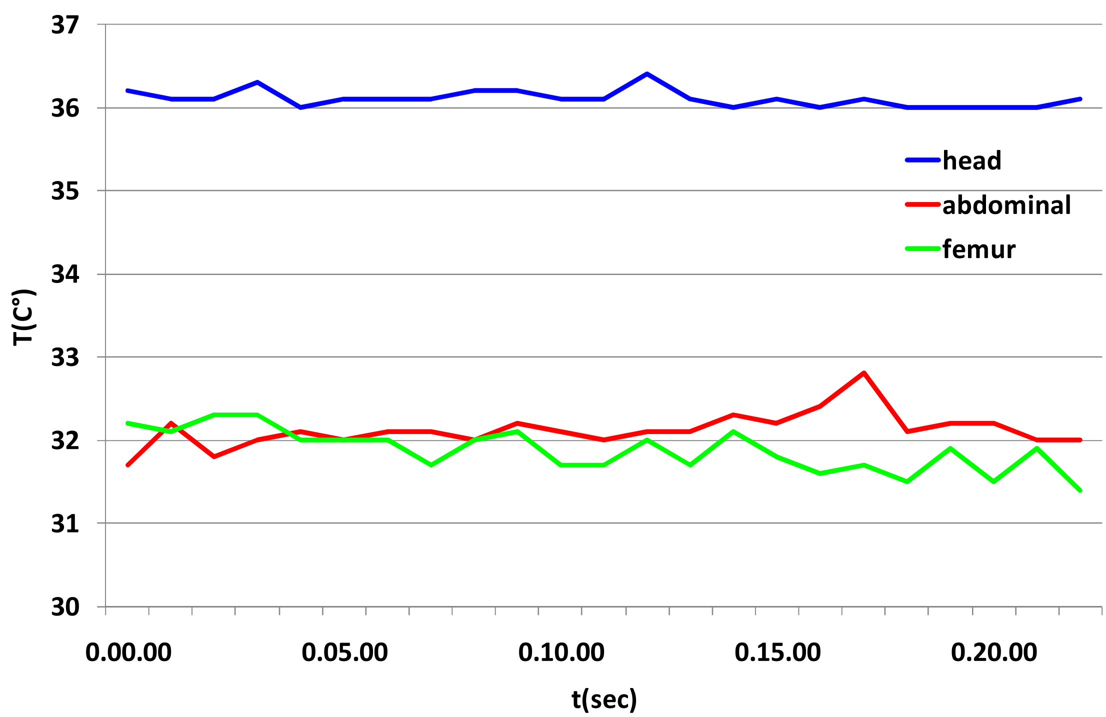

Figure 4 Superficial temperature variation of the head, the abdominal and the femur of the human body exposed to continuous vibration at a frequency of 45 Hz.

After the implementation of the experiments the initial hypothesis was rejected. This is because there was not significant energy expenditure of the human body in form of changes in the superficial temperature and in the oxygen uptake during the continuous vibration.

11.1.2 Intermittent vibrations

After rejecting the initial hypothesis, the *second step* was to investigate the response of the standing human body exposed to *intermittent vertical vibrations.*

The subjects performed a series of experiments on a vibrating plate in a standing position, varying the frequency and duration of the vibration exposure and the duration of rest period. The frequencies used were of 20, 25, 30 and 45 Hz. The exposure vibration period was not continuous but was replaced by five sets of vibrations (110 sec. each set) and a resting period lasting 60 sec. between each set. The rest period before and after the five sets of vibrations ranged from 5. to 15 min. The variation in superficial temperature and the oxygen uptake were measured during the vibration exposure period and the rest period before and after the vibrations. A sample of the oxygen uptake of the subjects during the experiment can be seen in the next three figures (Figs. 5,6,7). The duration of the exposure vibration time is indicated by the two dashed lines.

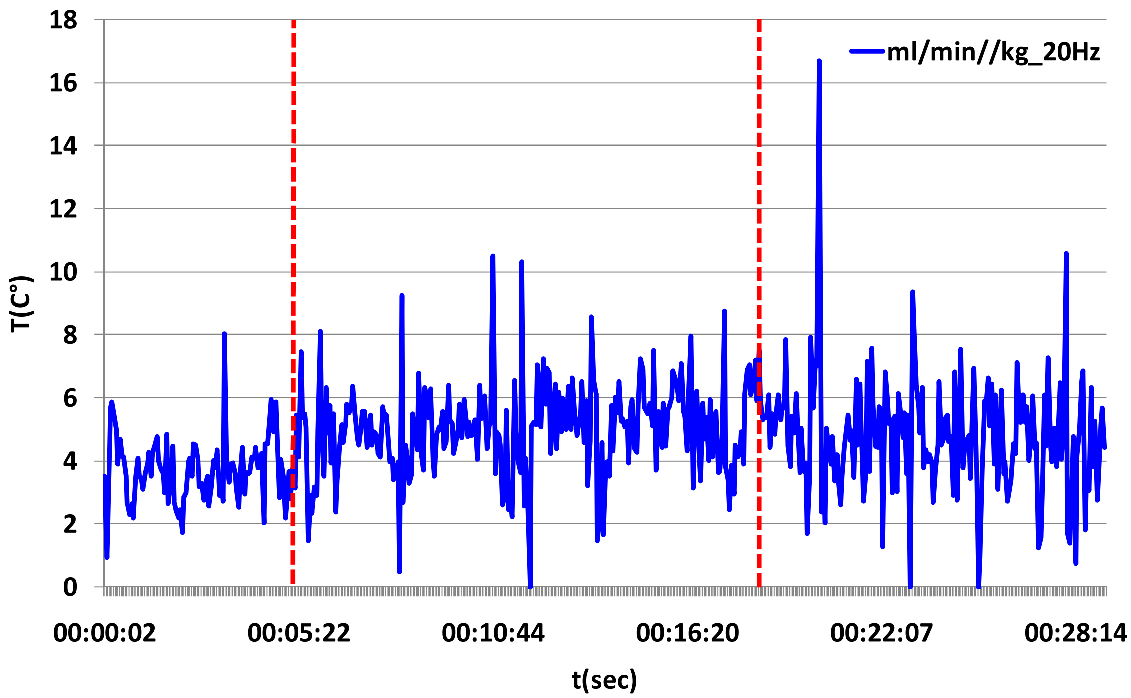

Figure 5 Oxygen uptake (ml/min/kg) of one of the subjects exposed to intermittent vibration at a frequency of 20 Hz. The dashed lines represent the start and the end of the whole 5 sets of vibrations.

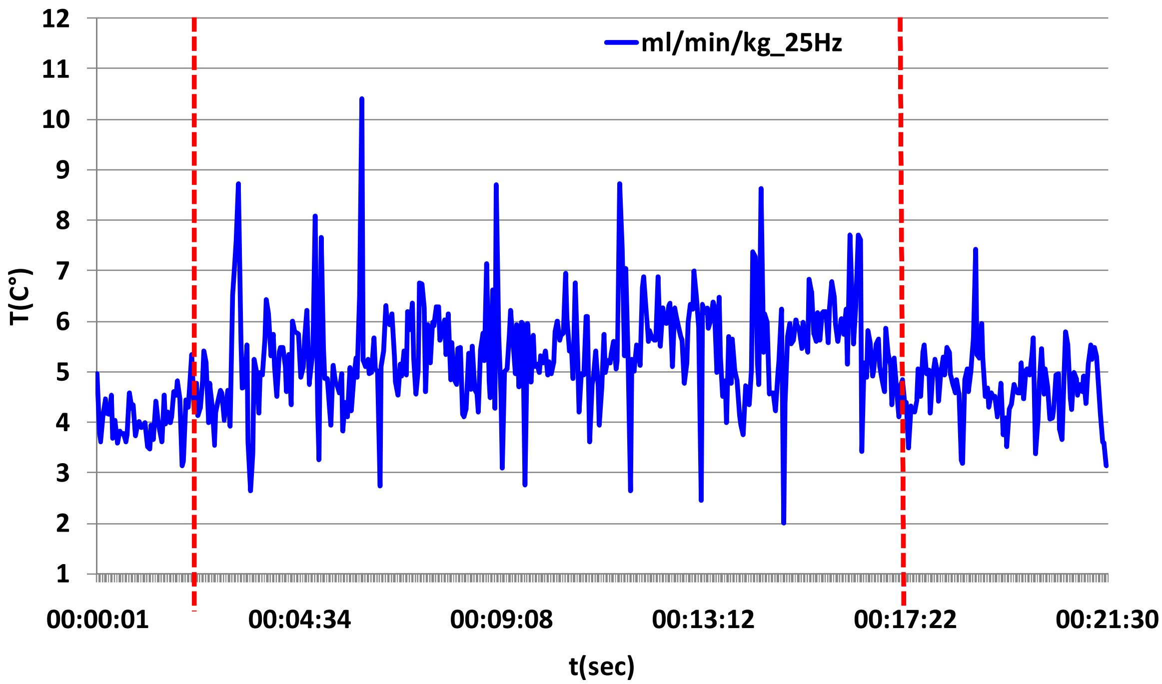

Figure 6 Oxygen uptake (ml/min/kg) of one of the subjects exposed to intermittent vibration at a frequency of 25 Hz. The dashed lines represent the start and the end of the whole 5 sets of vibrations.

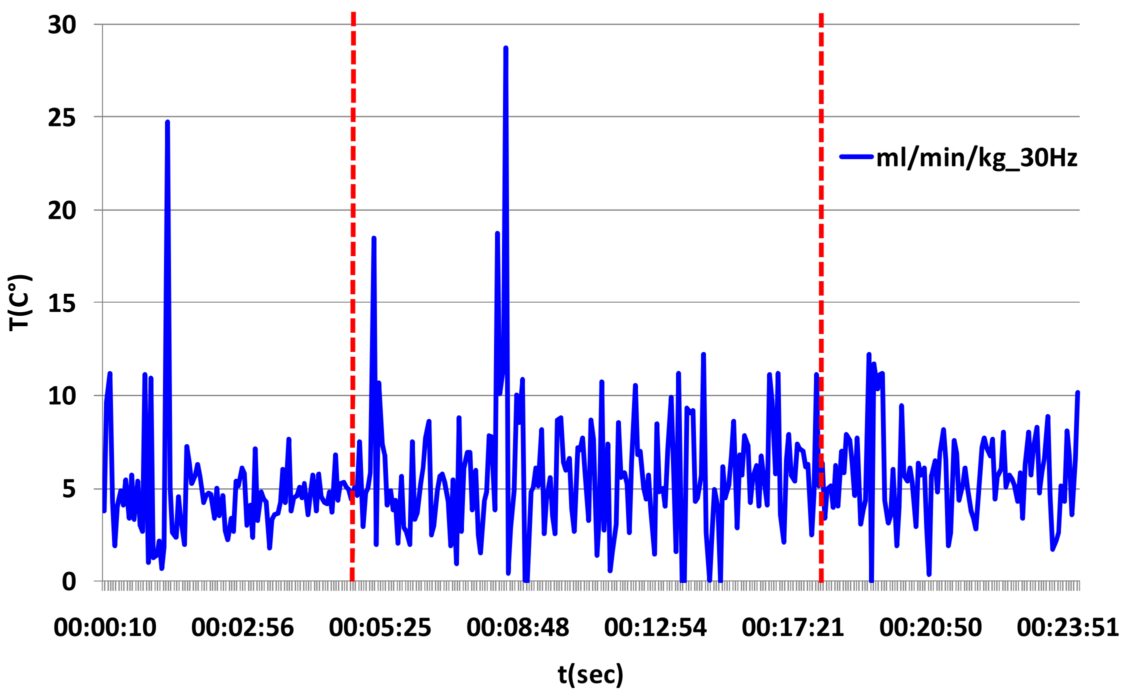

Figure 7 Oxygen uptake (ml/min/kg) of one of the subjects exposed to intermittent vibration at a frequency of 30 Hz. The dashed lines represent the start and the end of the whole 5 sets of vibrations.

Figs. 8,9,10 displays the variation of the human body superficial temperature during intermittent vibration at frequencies of 20, 25 and 30 Hz.

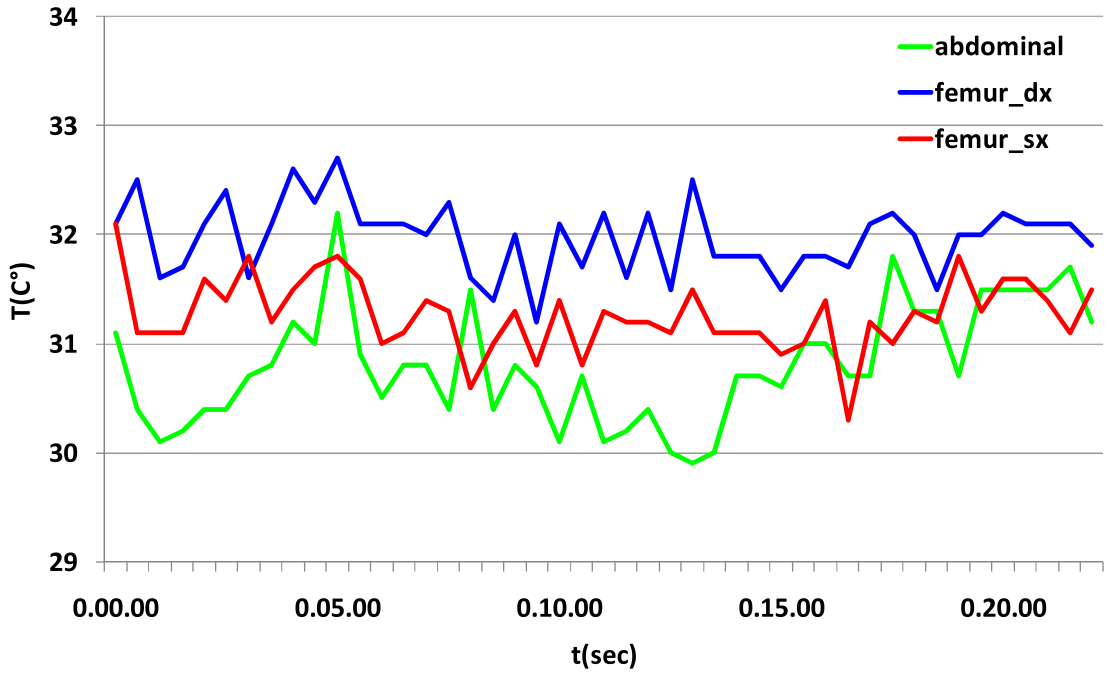

Figure 8 Superficial temperature variation of the abdominal, the right femur and the left femur of the human body exposed to intermittent vibration at a frequency of 20 Hz.

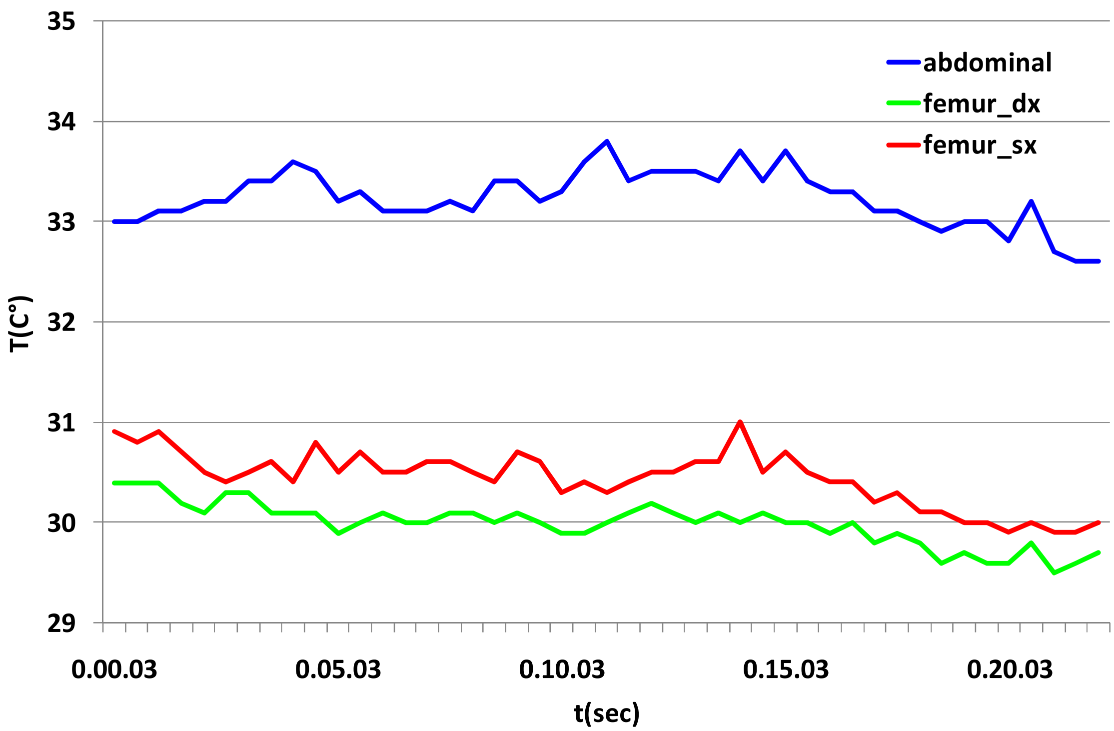

Figure 9 Superficial temperature variation of the abdominal, the right femur and the left femur of the human body exposed to intermittent vibration at a frequency of 25 Hz.

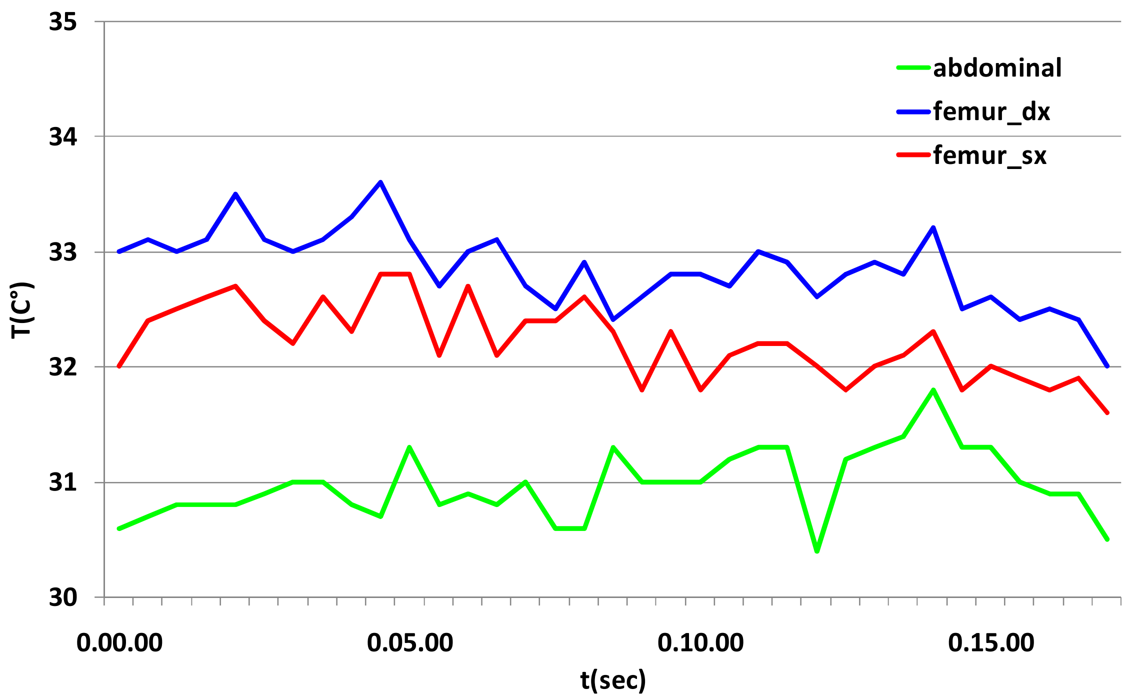

Figure 10 Superficial temperature variation of the abdominal, the right femur and the left femur of the human body exposed to intermittent vibration at a frequency of 30 Hz.

11.1.3 Evaluation of the results

The definition of an appropriate protocol, which satisfies the aim of this research, was the goal of the experimental setup. The response of the human body on continuous and intermittent vibrations changing the duration of vibration exposure, the duration of rest period and the frequency of vibration were examined. The *first hypothesis* was that there is a potential energy expenditure of the human body in form of changes in superficial temperature and in oxygen uptake during continuous vibration. The hypothesis was not confirmed by the results though. The *second hypothesis* was that there is a potential energy expenditure of the human body during intermittent vibration. The results confirmed the second hypothesis. In particular, the infrared thermography results and the oxygen uptake results showed a variation in superficial temperature of the human body and a raised oxygen consumption during intermittent vibration exposure. A significant variation of superficial temperature and a rise in the oxygen consumption was observed in the frequency of 25 Hz.

After taking into consideration the outcomes of the experimental setup, a final protocol was defined.

11.2 Final protocol

The final protocol has two key elements: the frequency and the duration as independent variables. These two elements are related to the vibration exposure and the rest period. The oxygen uptake and the superficial temperature of the human body were the dependent variables of this research.

Three different vibrations frequencies were chosen: 20, 30 and 45 Hz for three different tests. The rest period, before the vibration exposure, lasted 5 minutes and the rest period after the vibration exposure lasted 10 minutes. The vibration exposure consisted in five sets of vibrations (each set lasting 110 sec.) with a rest period between each test of 60 sec.

A linear relationship between the frequency of vibration exposure and the average oxygen consumption is found with a good approximation.

Two male subjects were used for these experiments. A vibrating table, two infrared thermography systems, the Cosmed K4 telemetric system and a Vicon MX motion system were used. The subjects were placed in a standing position on a vibrating table with 18 reflective markers and a Cosmed face mask and they performed the protocol.

The results of these experiments are shown in the next chapter.

References – Chapter 11

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CHAPTER 12

Fusion data and final results

After the establishment of the final protocol, a series of experiments took place in a laboratory. It was possible to assess the energy expenditure of the human body in a vibration environment by means of a global and integrated approach. In particular, the oxygen uptake, the variation of the superficial temperature and the displacement of the muscles were calculated and compared for three different vibration frequency values.

The measurement of oxygen consumption during the exposure to vibration can give important information for the energy expenditure of the subjects. Studies have shown that a vertical vibration in a frequency of 2 to 20 Hz of moderate to high magnitude, may lead to a cardiovascular response similar to the one normally occurring during moderate exercise. Heart rate, respiration rate, cardiac output, oxygen uptake and pulmonary ventilation all increase [1, 2]. Physiological stress or a raised metabolic activity caused by increased muscular activity, might be the major causes of such responses which are higher around frequencies of major body resonance and increase with an increasing vibration magnitude [3]. In another study [4], it is shown that vibration in the range 100-200 Hz, had no effect on the cardiovascular or respiratory system. Duffner showed [5] that during exposures of 4 min. to vertical whole-body vibration an initial hyperventilation with rapid return to normal is presented. Other studies report that the respiratory air flow and oxygen uptake increase with the vibration magnitude, but the size of the increase has often been small unless high vibration magnitudes were used. In a study by Rittweger [6], whole-body vibration to exhaustion with an extra weight showed an O_2 uptake of less than 50% of VO_2max.

Estimating the variation of superficial temperature of the human body with the aid of infrared thermography, it is possible to obtain interesting results regarding how the human body behaves under different vibration conditions. Many studies showed that vibratory simulation can cause a local fall in superficial temperature of the body [7-9] due to vasoconstriction caused by the tonic vibration reflex, but the temperature change is not always observed. Other studies have reported increased body temperature of animals on prolonged exposure to whole-body vibration [10].

Measurement of the displacement, velocity and acceleration of the human muscle during the vibration exposure could give interesting information about the behaviour of the human muscle in a vibrating environment.

In this study, it was possible to estimate many interesting parameters connected with the experimental results. Results related to the changes in superficial temperature, the oxygen uptake and the displacement of the human segments are exposed in the following paragraphs.

12.1 Motion capture results

Measurement of the transmission of vertical vibration on the human body can be done by mounting accelerometers on the surface of the skin above bony landmarks or other anatomical locations.

In this research, a 4-camera Vicon MX motion system was used for the acquisition of displacement data of human muscles. Two male subjects were instrumented with photo-reflective markers. The resolution of acquisition was 200 Hz. Eighteen markers were placed in critical points of interest.

All the data were collected from the photo-reflective markers through the 4 cameras in the computer and a first data elaboration was possible with the Vicon MX motion system. The model of the human body was created and all the eighteen markers were reported.

Some results of the acceleration history motion in Vicon MX motion system can bee seen in Fig. 1.

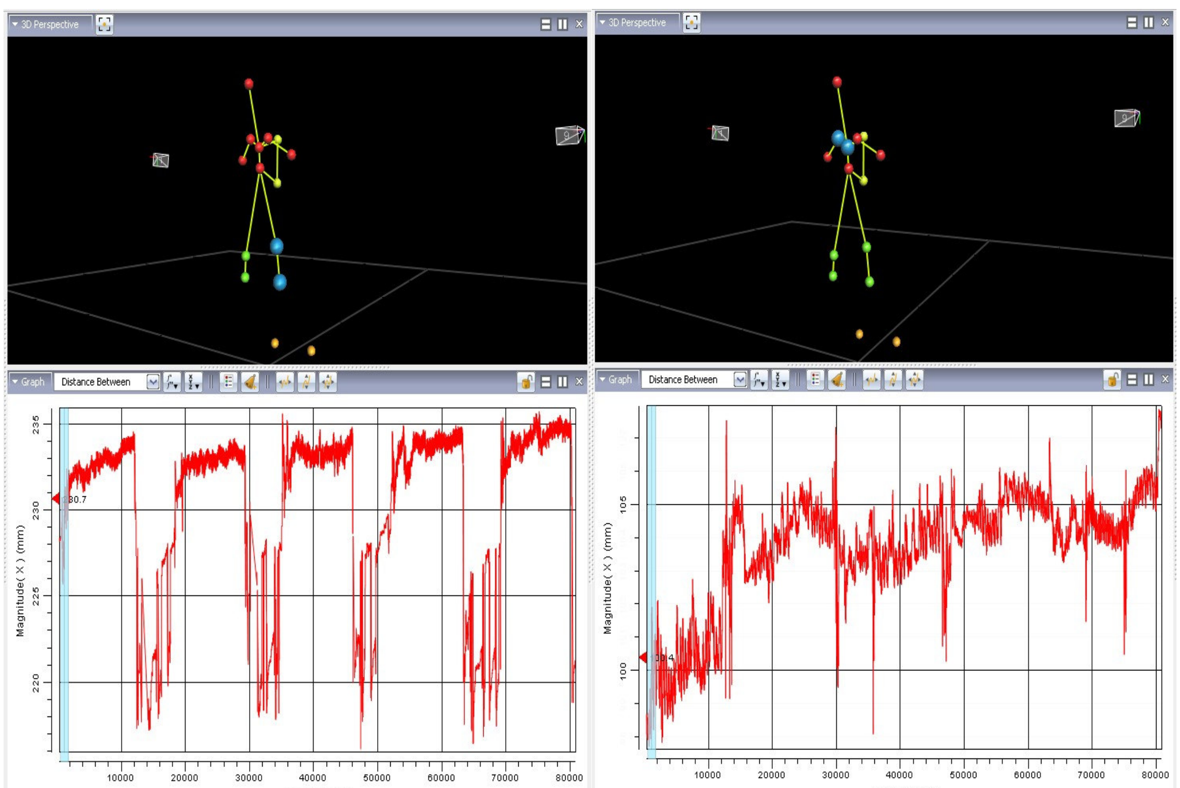


Figure 1 Model of the human body in the Vicon MX motion system.

Fig. 2 displays the two male subjects positioned in the vibration environment with the 18 reflective markers and the Cosmed face mask.

Measurements of acceleration at a location of the body (e.g. femur, head) can be compared to those at the vibrating table and are usually expressed in terms of *transmissibility*.

The ratio of the amplitude of the force transmitted to the human body to that of the exciting force gives significant information for the amplitude transmissibility into the human joints and the assessment of the isolation efficiency of the human body. Subject weight and size, leg position and foot-support position may influence the measured transmissibility.

Figure 2 The two subjects positioned in the vibrating standing position.

In this research, the ratio of the amplitude of the force transmitted to the ankle, the femur, the abdominal and the head to that of the exciting force was measured.

The vertical transmissibility from the vibrating table to three different locations on the human body is shown in Figs. 3-4.

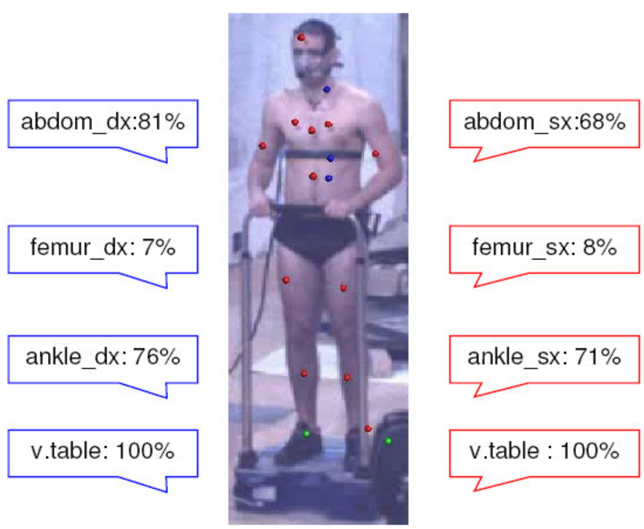


Figure 3 Vertical (z-axis) transmissibility at three locations of the human body (subject 1). Input motion at a frequency of 45 Hz.

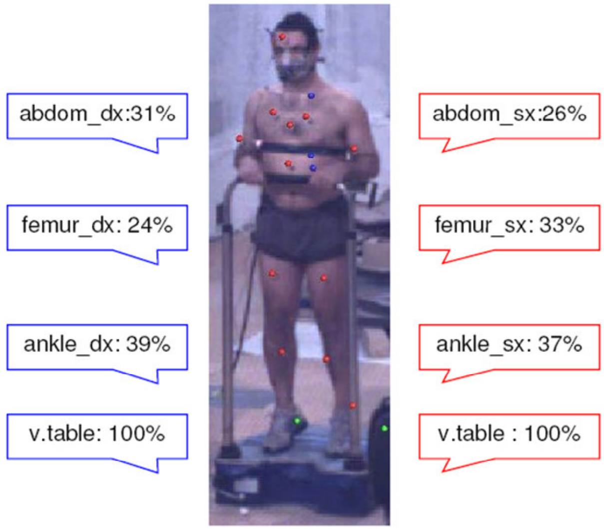


Figure 4 Vertical (z-axis) transmissibility at three locations on the human body (subject 2). Input motion at a frequency of 45 Hz.

The ratio of acceleration, in terms of root-mean-square acceleration (ms^{-2}), of a location of the human body to those of the vibrating plate was measured, and the absolute transmissibility coefficients were obtained. Moreover, the ratio of acceleration of a location of the human body to the previous one was measured and the relative transmissibility coefficients were obtained.

The relative and absolute transmissibility coefficients and the relative and absolute dispersion coefficient (complement to 1 of the transmissibility coefficient) of some location of the subjects at a frequency of 45 Hz are shown in Tables 1and 2.

Table 1 Transmissibility and dispersion coefficient of subject 1.

Human body segments (subject 1)	Absolute Transmissibility Coefficient	Absolute Dispersion Coefficient	Relative Transmissibility Coefficient	Relative Dispersion Coefficient
Ankle_dx	0,76	0,24	0,76	0,24
Ankle_sx	0,71	0,29	0,71	0,29
Femur_dx	0,05	0,95	0,07	0,93
Femur_sx	0,06	0,94	0,08	0,92
Abdominal_dx	0,04	0,96	0,78	0,22
Abdominal_sx	0,04	0,96	0,68	0,32
Head_dx	0,07	0,93	1,30	-
Head_sx	0,06	0,94	1,01	-

Table 2 Transmissibility and dispersion coefficient of subject 2.

Human body Segments (subject 2)	Absolute Transmissibility Coefficient	Absolute Dispersion Coefficient	Relative Transmissibility Coefficient	Relative Dispersion Coefficient
Ankle_dx	0,39	0,61	0,39	0,61
Ankle_sx	0,37	0,63	0,37	0,63
Femur_dx	0,09	0,91	0,24	0,76
Femur_sx	0,12	0,88	0,33	0,67
Abdominal_dx	0,02	0,98	0,31	0,69
Abdominal_sx	0,03	0,97	0,26	0,74
Head_dx	0,10	0,90	1,10	-
Head_sx	0,11	0,89	0,91	-

As assumed before, the leg and food position may influence the transmissibility so it could be wise to recognise that the transmission of vertical vibration to the human body from the vibrating table could be influenced by a variety of such postural factors.

In both subjects, there is no dispersion of vertical vibrations from the vibrating table to the head. This should be related with the morphology (rigidity) of the head and the fact that there is no vertical dispersion through the bones, since the vibration is transmitted directly to the head through the vertebral column.

Figs. 5-6 shows the power spectra of vertical vibration in z-axis on the human body (subject 1) via the ankle, the abdominal and the head with a frequency of 30 Hz. It can be observed in these figures that the ankle acceleration is of a greater magnitude than the one of the head indicating a vibration damping effect or shielding by the human joint reactions.

From the graphs it can be ascertained that there is a major displacement of the head and ankle far above the abdominal displacement. Also, the graphs indicates that the vibrations of these segments are much less than the input vibration of the vibrating table indicating a large amount of damping or energy release between the vibrating table and the body segments.

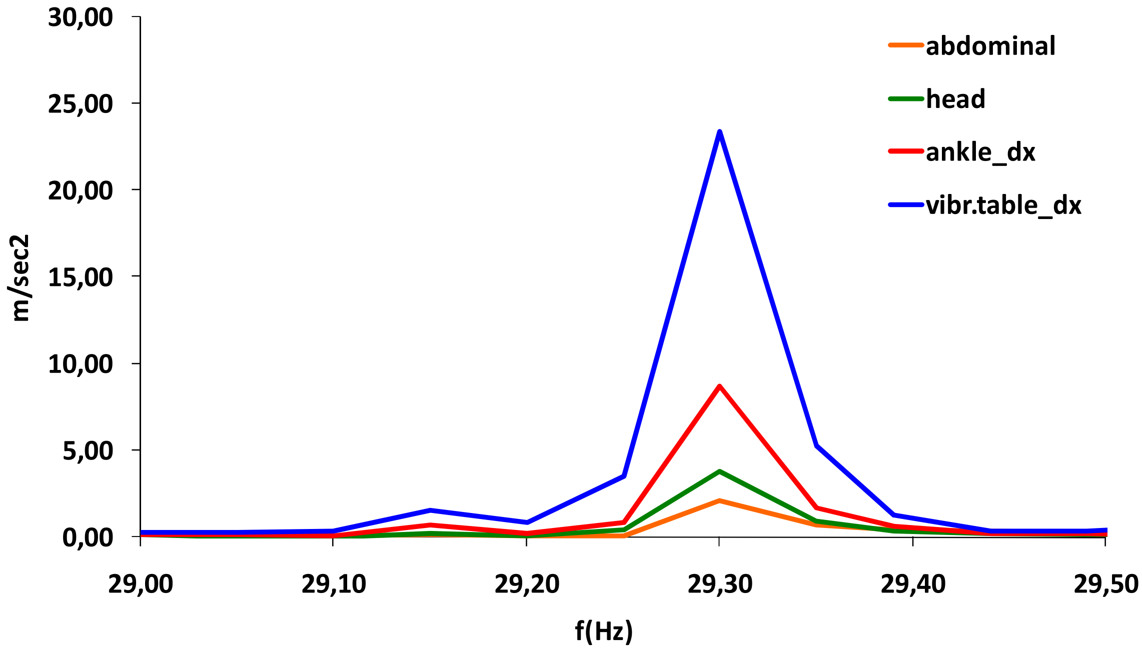


Figure 5 Spectral of vertical (z-axis) vibration on the abdominal, the head, the right ankle of the human body (subject 1) and on the right part of the vibrating table.

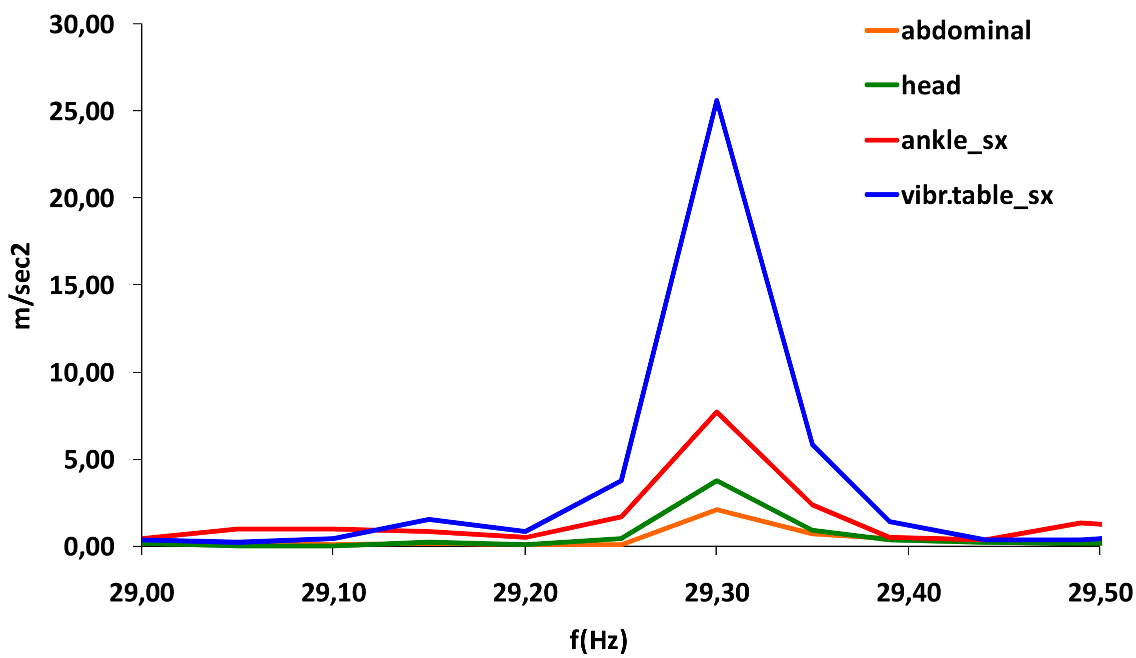


Figure 6 Spectral of vertical (z-axis) vibration on the abdominal, the head, the left ankle of the human body (subject 1) and on the left part of the vibrating table.

Figs. 7-8 displays the power spectra of vertical vibration in z-axis on the human body (subject 2) via the ankle, the femur, the abdominal and the head with a frequency of 20 Hz.

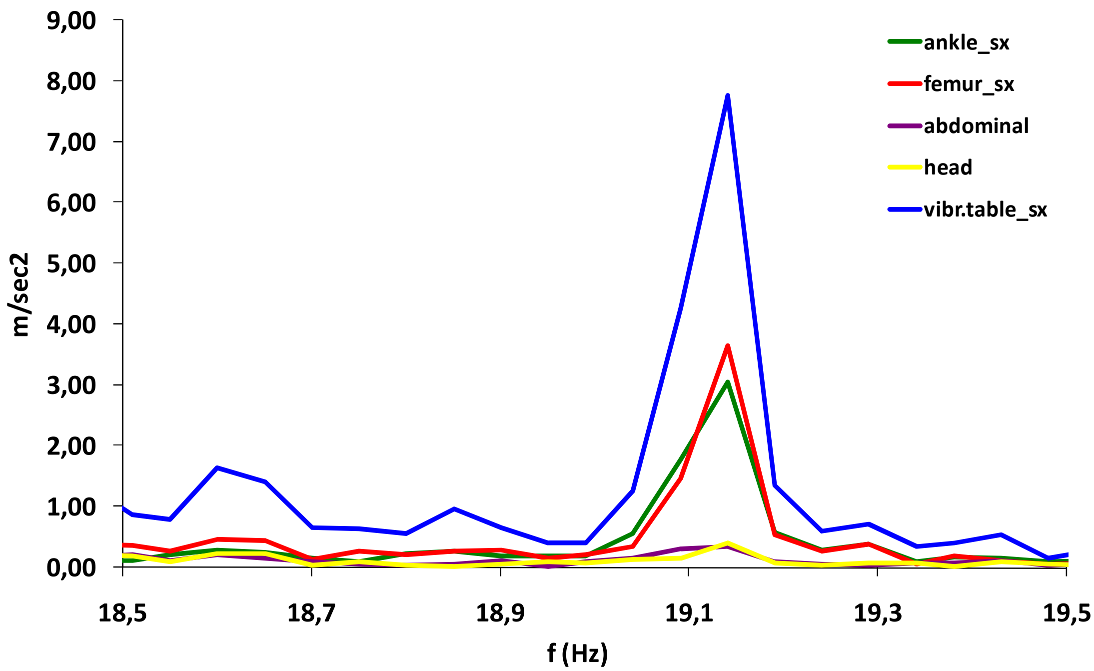


Figure 7 Spectral of vertical (z-axis) vibration on the abdominal, the head, the left ankle, left femur of subject 2 and of the marker placed on the left part of the vibrating table.

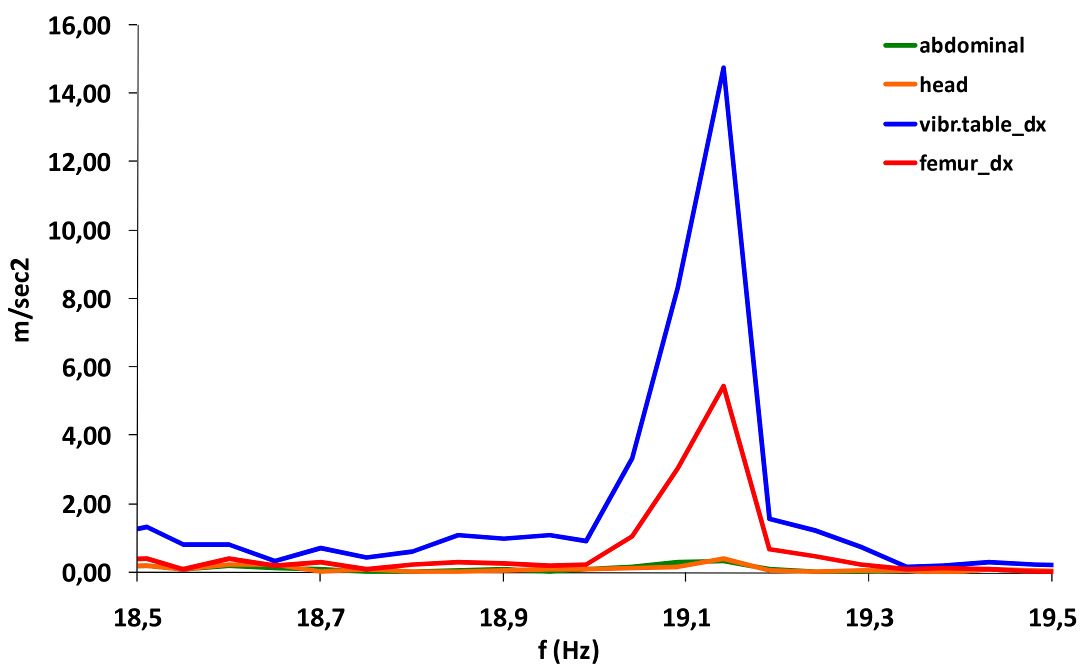


Figure 8 Spectral of vertical (z-axis) vibration on the abdominal, the head, the right femur of subject 2 and of the marker placed on the right part of the vibrating table.

From the graphs it can be seen that there is a major displacement of the femur and the ankle far above the abdominal and the head displacement. As we saw in Figs. 5-6, also these graphs shows that the vibrations of these body segments are much less than the input vibration of the vibrating table indicating a large amount of damping or energy release between the vibrating table and the body segments.

12.2 Oxygen uptake results

In this study, the telemetric system Cosmed K4 was used to estimate the energy expenditure of the subjects by means of oxygen uptake (VO_2 and VCO_2 were measured). This system was used during the whole experiment and oxygen uptake data were registered during the vibration exposure and the rest periods before and after the vibrations.

Fig. 9 displays the variation of the oxygen uptake of subject 1 at three different frequencies (20, 30, 45 Hz) in function of time.

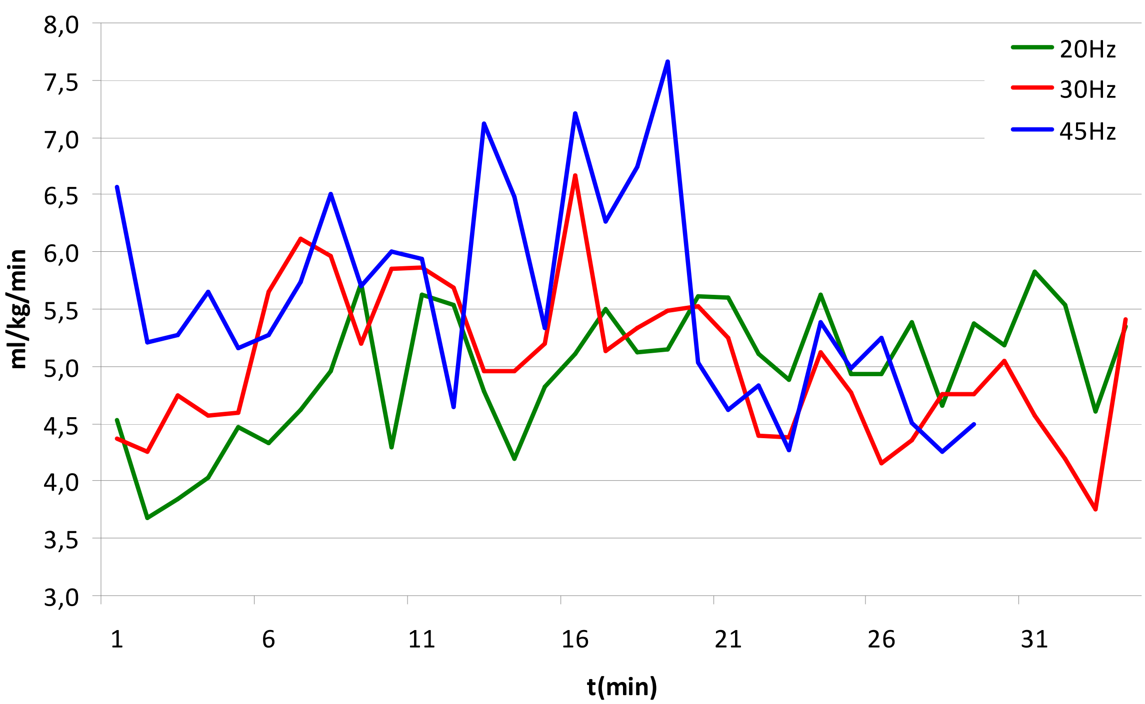


Figure 9 Oxygen uptake of subject 1 at frequencies: 20 Hz, 30 Hz and 45 Hz.

Fig. 10 shows the variation of the oxygen uptake of subject 2 at two different frequencies (20, 45 Hz) in function of time.

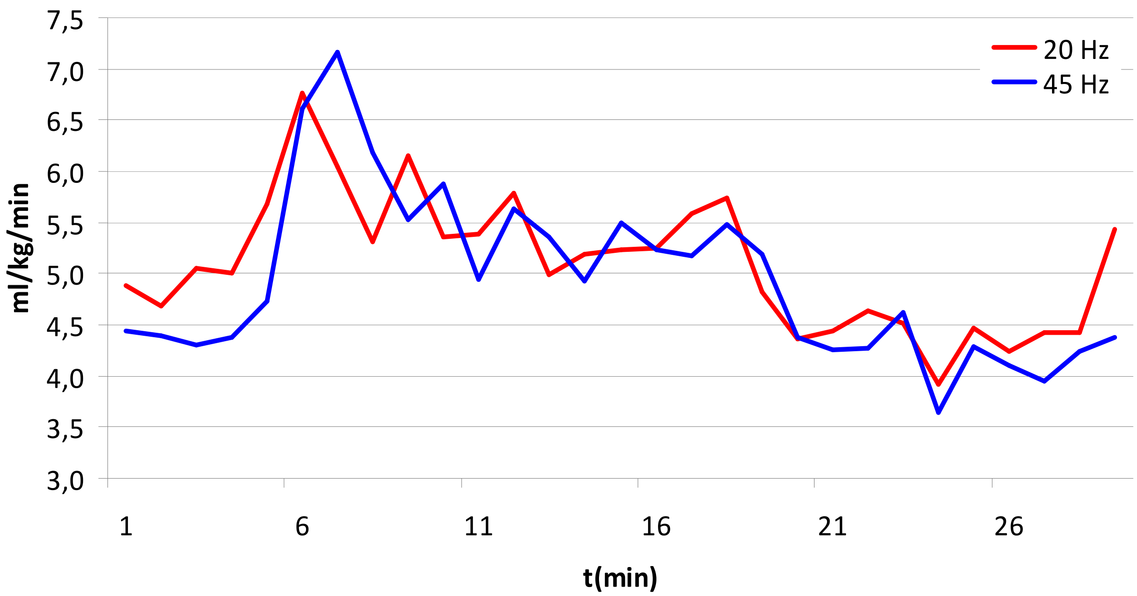


Figure 10 Oxygen uptake of subject 2 at frequencies: 20 Hz and 45 Hz in function of time.

It has been shown that vertical vibrations can cause variations in respiratory flow. In particular, an increase in oxygen consumption is presented at highest frequencies (45 Hz). An initial hyperventilation was found during the period of vertical vibrations with a rapid return to normal after the vibration period. However, the size of the increased respiratory air and oxygen uptake has been small at all the frequencies.

12.3 Thermographic results

Two infrared thermography cameras were used in this study to estimate the variation of superficial temperature of the human body during the experiments.

At the beginning of each experiment an ambient temperature of 23°C and a body temperature of around 37°C were guaranteed. Then, data results (thermal images) were collected from the three phases of the experiment (rest period before vibration exposure, vibration period, rest period after vibration exposure) and data analysis of the thermal images on a computer were performed.

The changes in superficial temperature of subject 1 during the experiment in vibrating frequencies of 20, 30 and 45 Hz are shown in the next figures (Figs. 11-13).

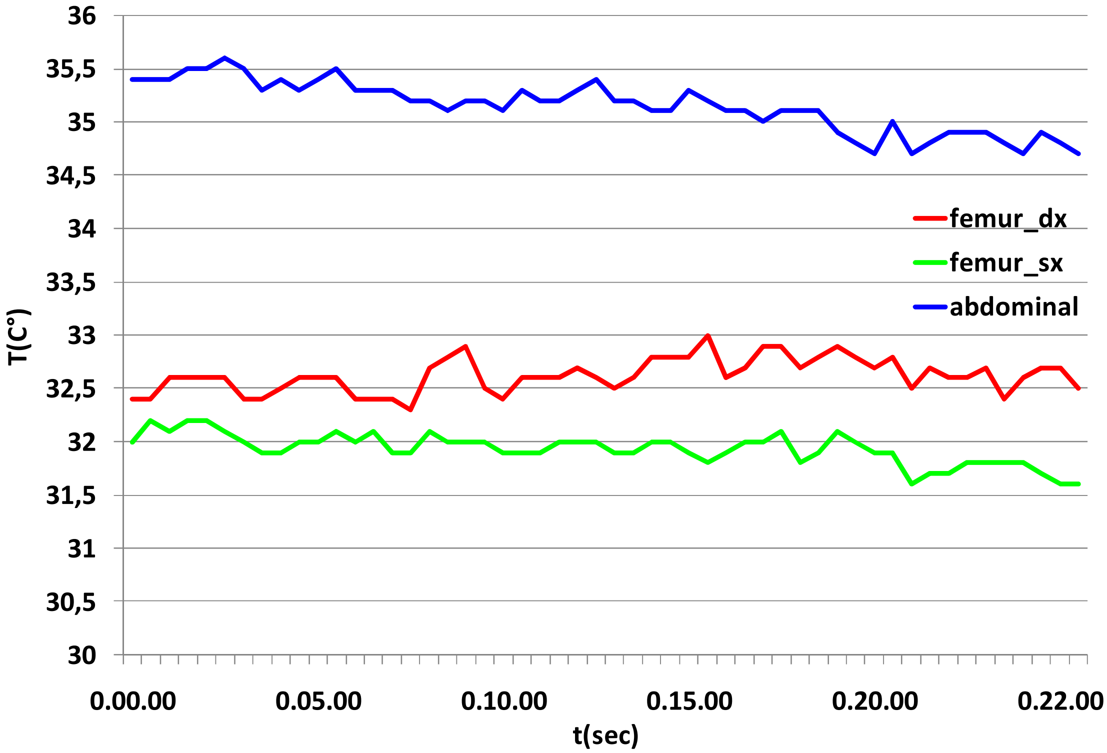


Figure 11 Time course of superficial temperature of the right femur (red line), of the left femur (green line) and of the abdominal (blue line) of subject 1 at vibrating frequency of 20 Hz.

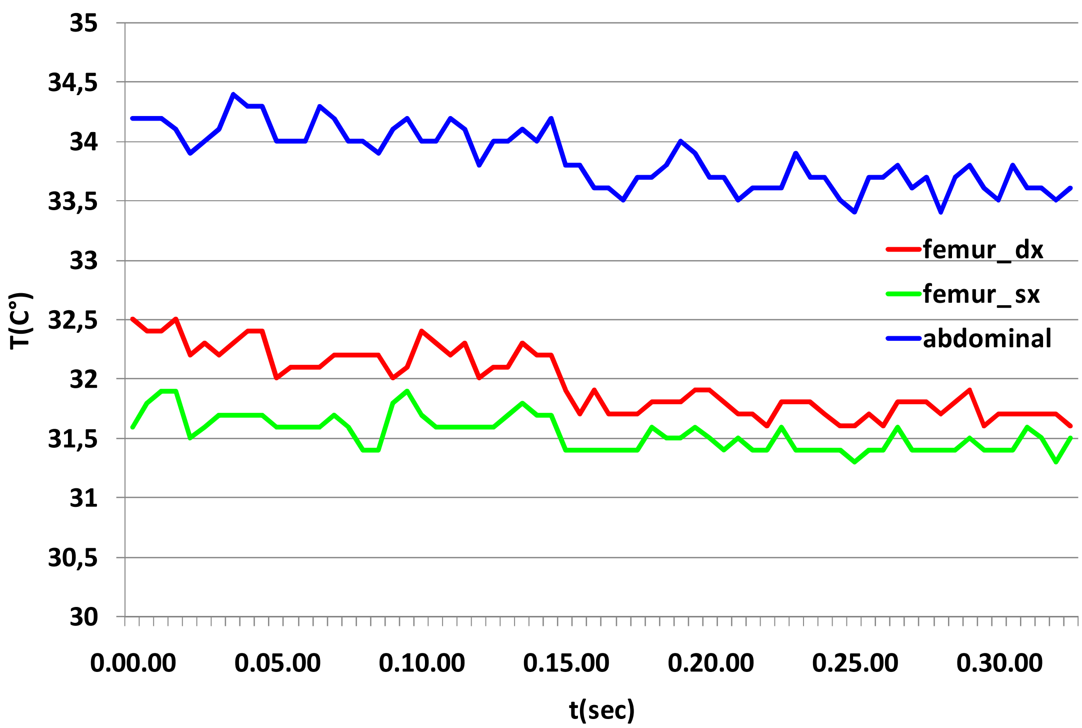


Figure 12 Time course of superficial temperature of the right femur (red line), of the left femur (green line) and of the abdominal (blue line) of subject 1 at vibrating frequency of 30 Hz.

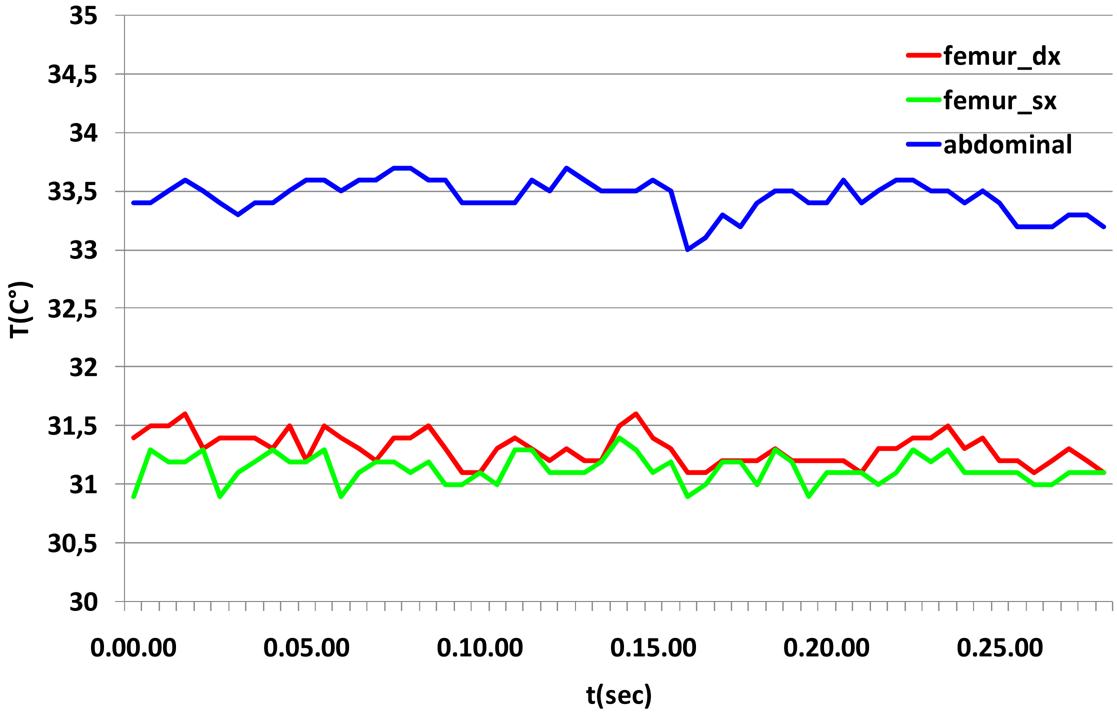


Figure 13 Time course of superficial temperature of the right femur (red line), of the left femur (green line) and of the abdominal (blue line) of subject 1 at vibrating frequency of 45 Hz.

As can be seen from Figs. 11-13, there is an evident fall in the superficial temperature of the abdominal, the right and the left femur of subject 1 at the frequency of 30 Hz. At the frequency of 20 Hz there is a fall in the superficial temperature of the abdominal, a small fall in the superficial temperature of the left femur and a small increase in the superficial temperature of the right femur. Also, there is no significant change in the superficial temperature of subject's body at the frequency of 45 Hz in both the three locations.

The next figures (Figs. 14-15) display the changes in superficial temperature of the human body (subject 2) in three locations during the experiment at frequencies of 20 and 45 Hz.

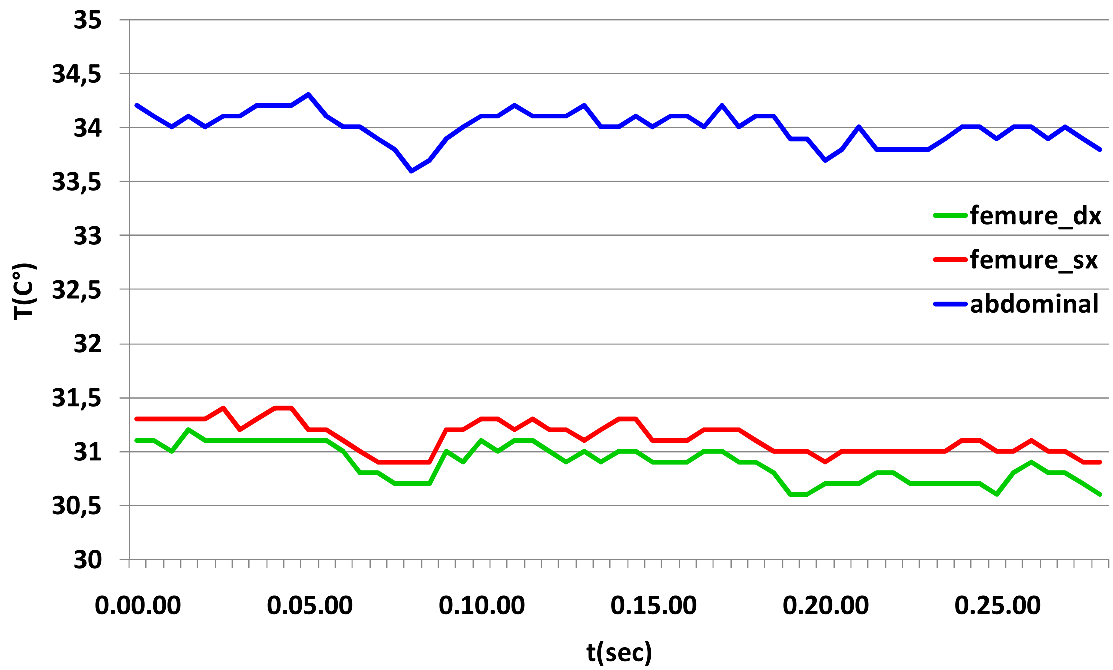


Figure 14 Time course of superficial temperature of the right femur (green line), of the left femur (red line) and of the abdominal (blue line) of subject 2 at vibrating frequency of 20 Hz.

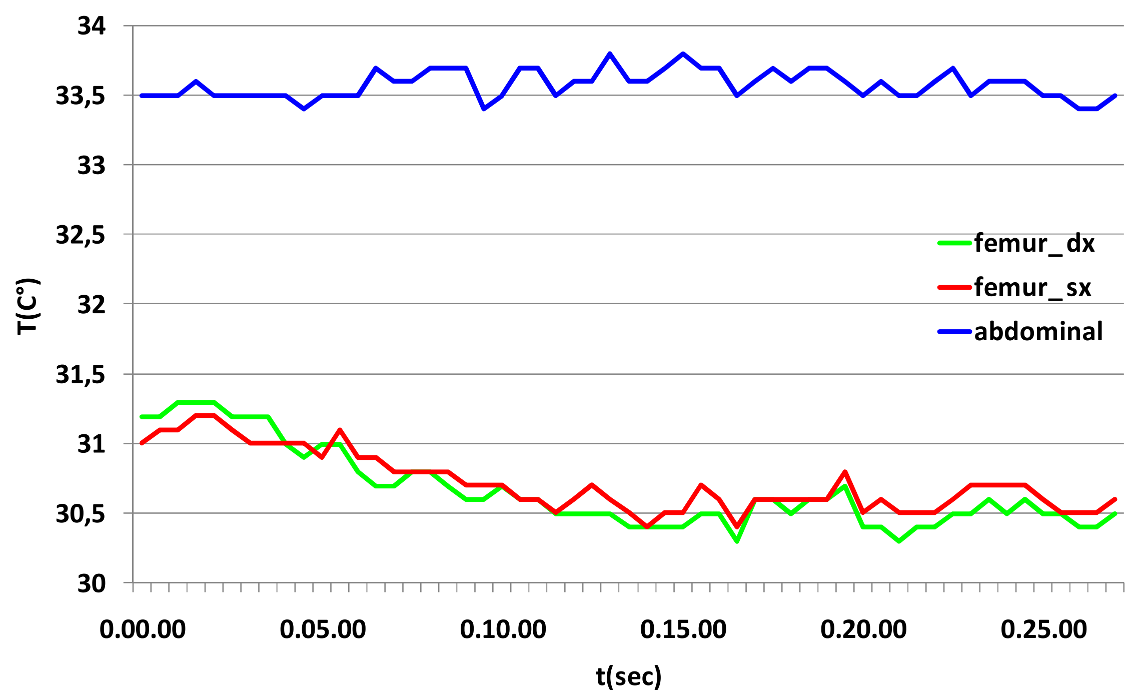


Figure 15 Time course of superficial temperature of the right femur, the left femur and of the abdominal of subject 2 at a vibrating frequency of 45 Hz.

Fig. 14 display a small fall in the superficial temperature of the abdominal, of the left and of the right femur (subject 2) at the frequency of 20 Hz. At a vibrating frequency of 45 Hz (Fig. 15), there is no change in the superficial temperature of the abdominal but a small initial fall and a following stabilization in the superficial temperature of the right and left femur of subject 2.

Fig. 16 displays the change of superficial temperature of the right femur (subject 1) during the experiment exposed to vertical vibration at frequency of 20, 30 and 45 Hz.

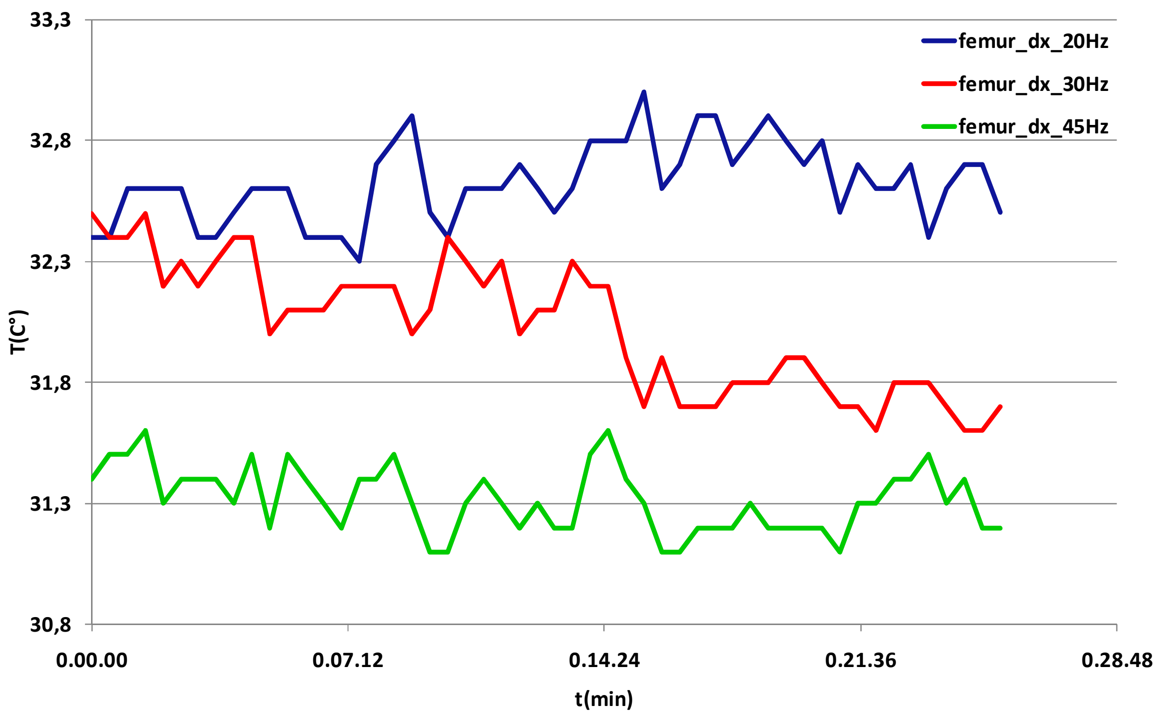


Figure 16 Time course of superficial temperature of the right femur (subject 1) at frequencies of 20 (blue line), 30 (red line) and 45 (green line) Hz.

Fig. 17 displays the change in superficial temperature of the left femur (subject 1) during the experiment exposed to a frequency of 20, 30 and 45 Hz vertical vibration. Fig. 18 shows the variance in superficial temperature of the abdominal (subject 1) at the frequencies of: 20, 30 and 45 Hz during the whole experiment..

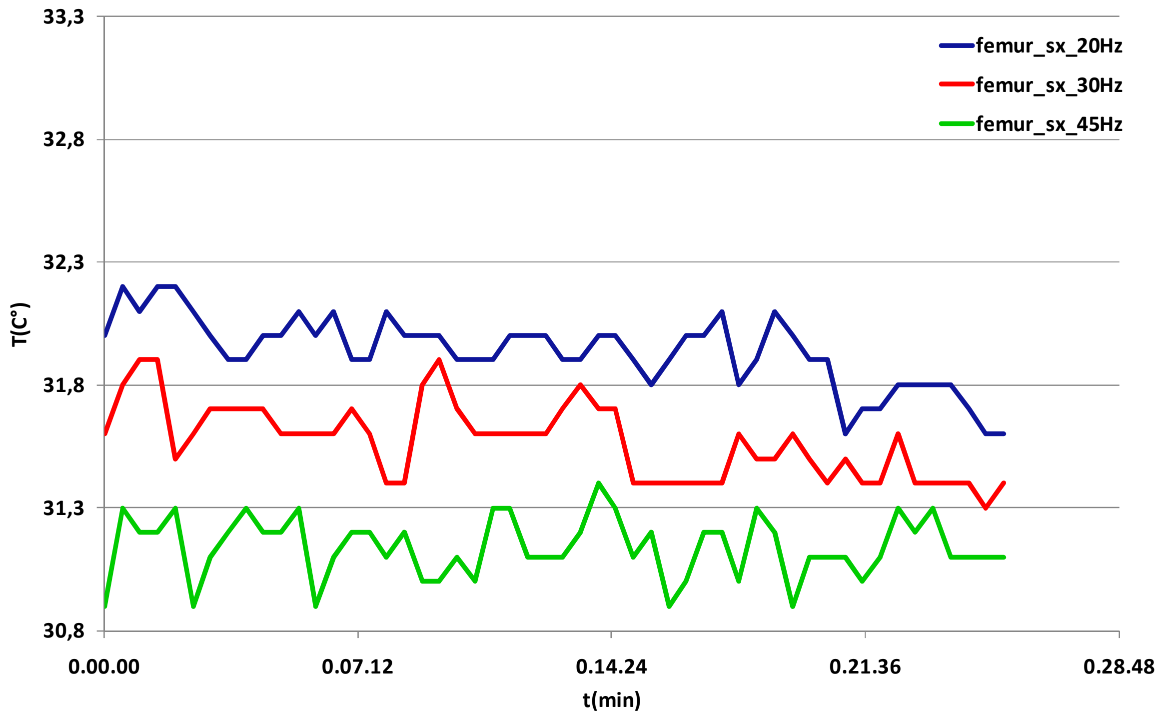


Figure 17 Time course of temperature of the left femur (subject 1) at frequencies of 20, 30 and 45 Hz.

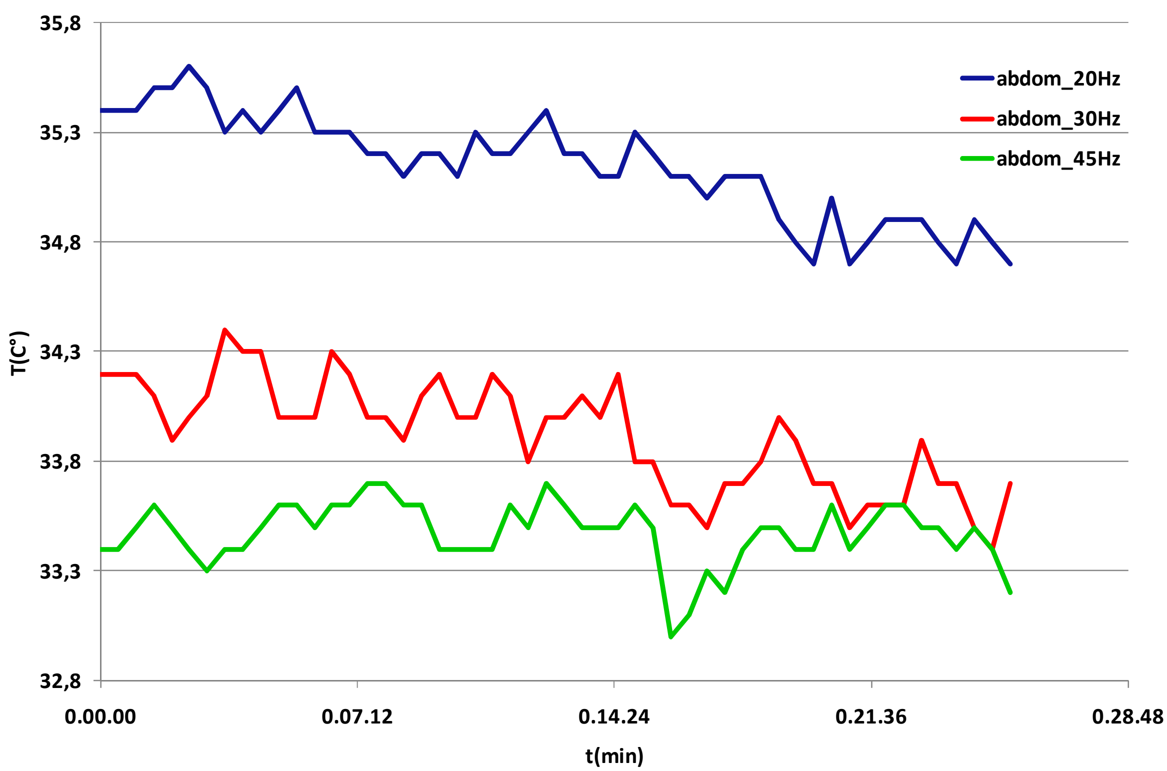


Figure 18 Time course of superficial temperature of the abdominal (subject 1) at frequencies of 20, 30 and 45 Hz.

The next three figures (Figs. 19-21) display the changes in superficial temperature of the right femur, the left femur and the abdominal of subject 2 at a frequency of 20 and 45 Hz.

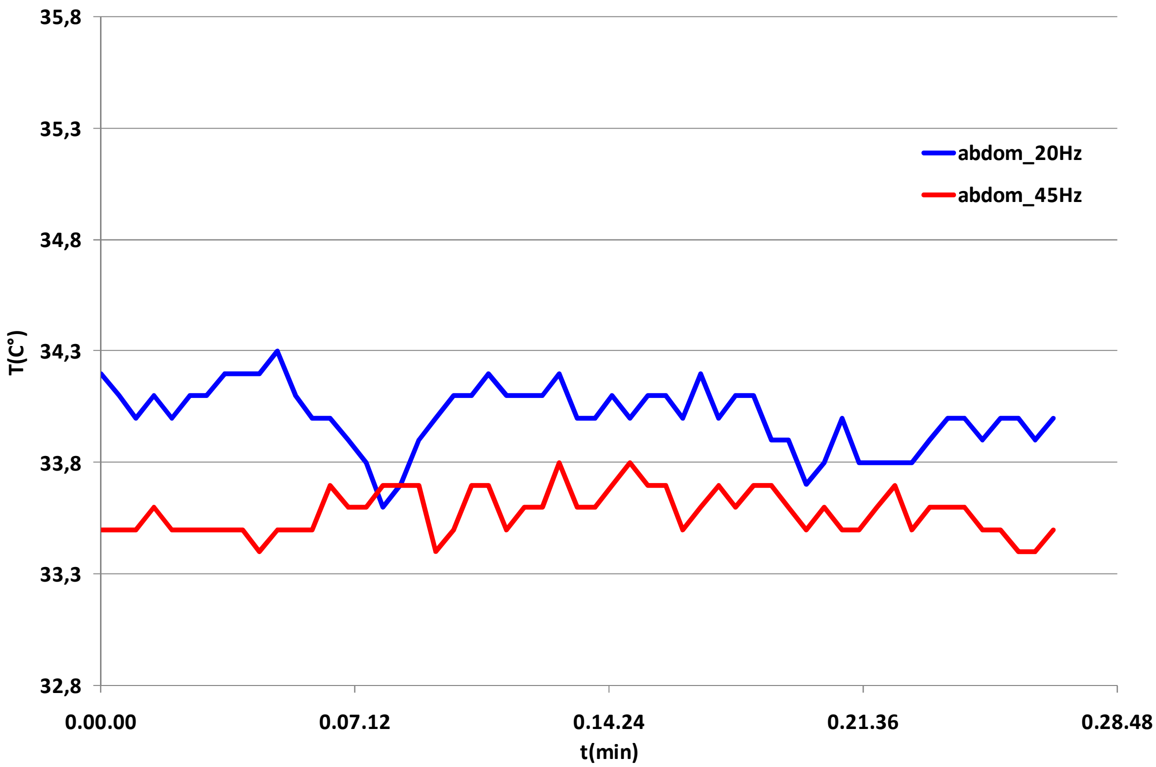


Figure 19 Time course of superficial temperature of the abdominal (subject 2) at frequencies of 20 and 45 Hz.

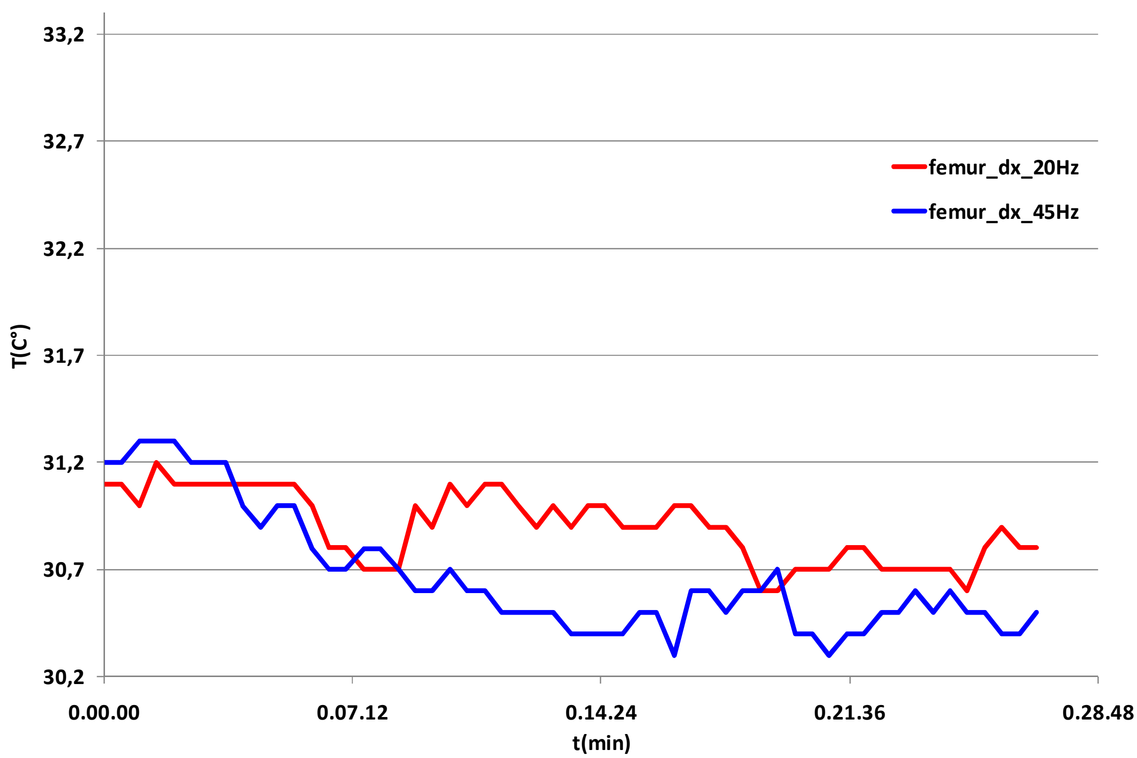


Figure 20 Time course of superficial temperature of right femur (subject 2) at frequencies of 20 and 45 Hz.

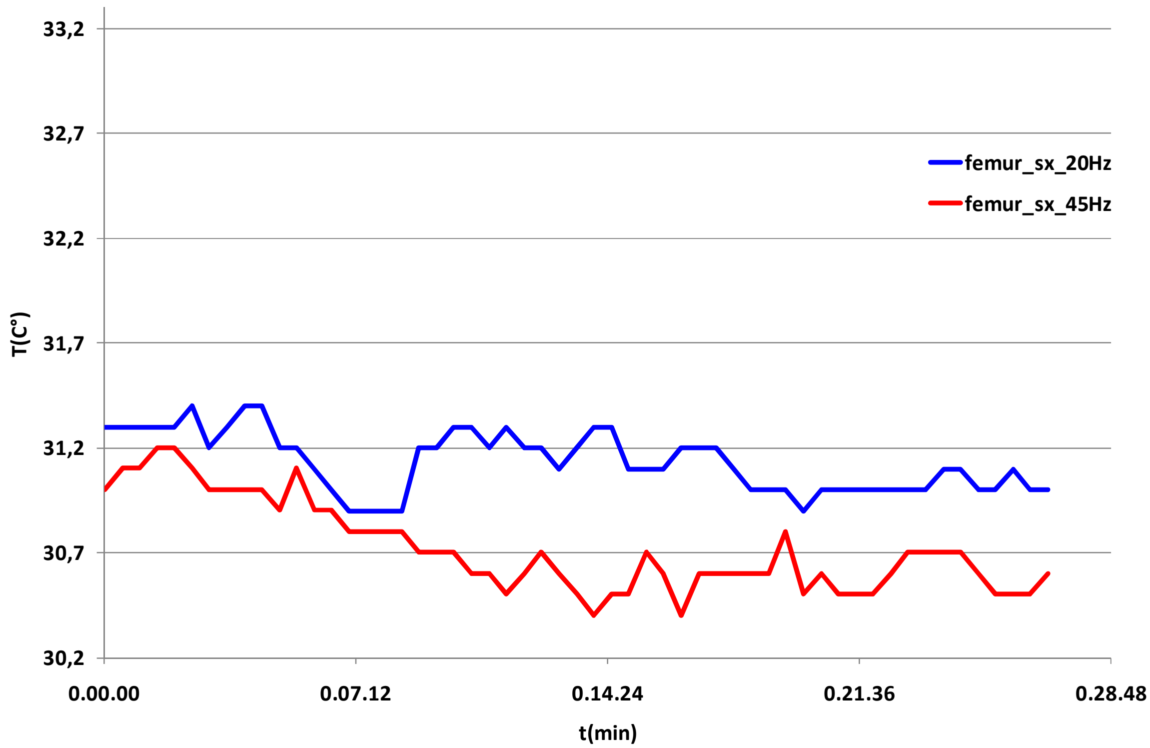
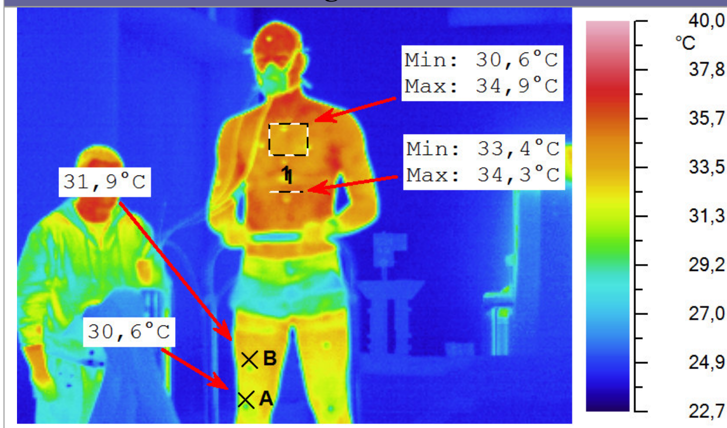


Figure 21 Time course of superficial temperature of left femur (subject 2) at frequencies of 20 and 45 Hz.

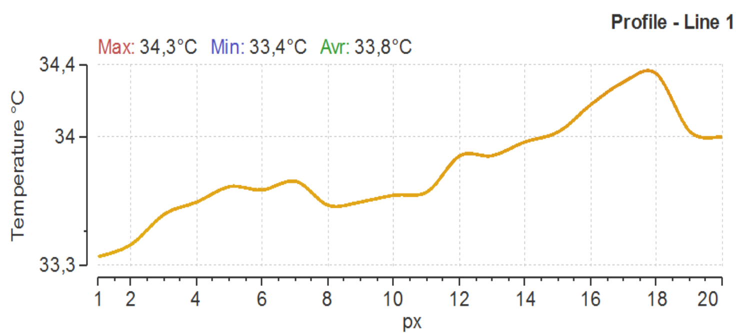
Some thermographic results related to the superficial temperature response of subjects 1 in a vibrational environment at frequencies of : 20, 30 and 45 Hz are display in the following reports.

Subject 1	
Freq (vibr.tab)	20 Hz
No. jpg	IR_3368.jpg

Thermal Image	Vision Image



Curve showing temperatures of every line point



Temperature values at points

Point	T °C	Emis.	Ta °C
A	30,6°C	0,93	23,0
B	31,9°C	0,93	23,0

Working conditions

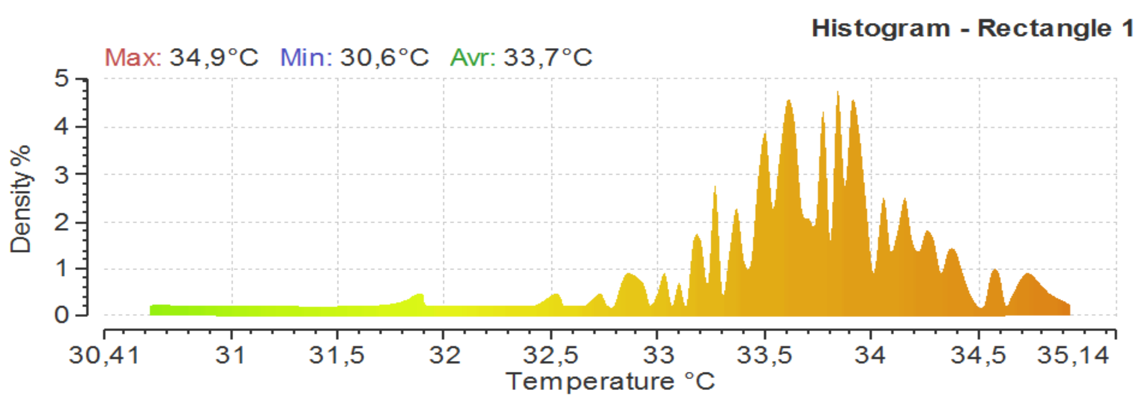
Range of thermography:

Tmax: 36C°, Tmin: 22C°

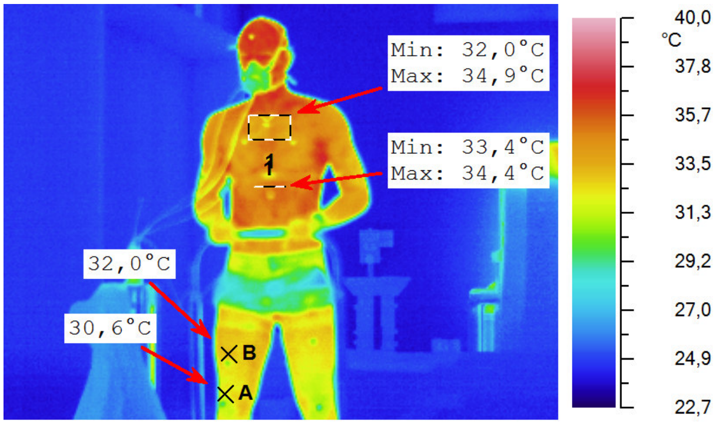
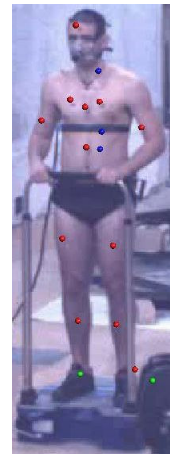
Humidity:

Tamb: 23C°

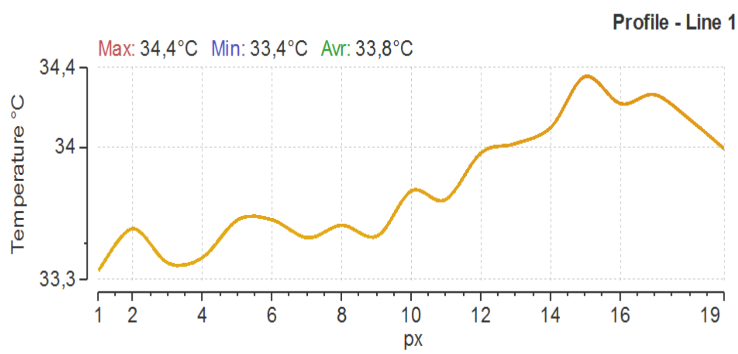
Histogram: thermal information about rectangle 1



Subject 1	
Freq (vibr.tab)	20 Hz
No. jpg	IR_3376.jpg

Thermal Image	Vision Image
	

Curve showing temperatures of every line point



Temperature values at points

Point	T °C	Emis.	Ta °C
A	30,6°C	0,93	23,0
B	32,0°C	0,93	23,0

Working conditions

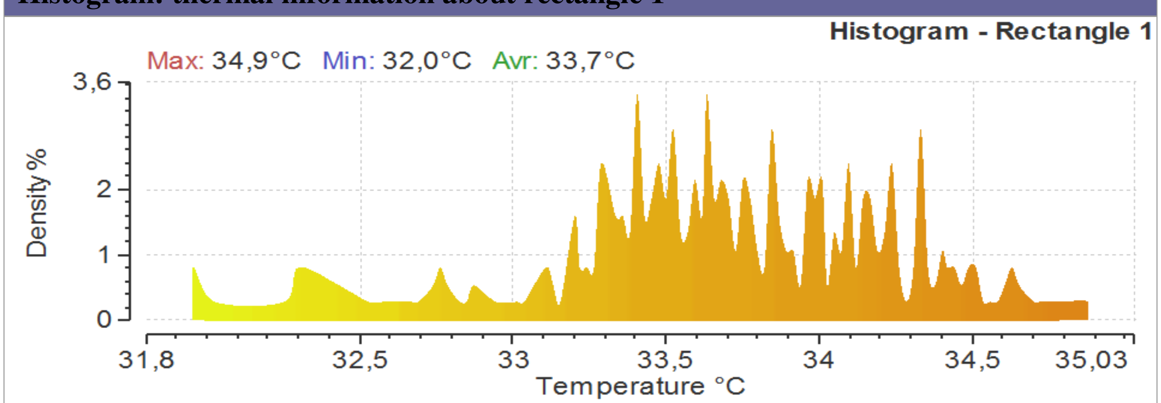
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

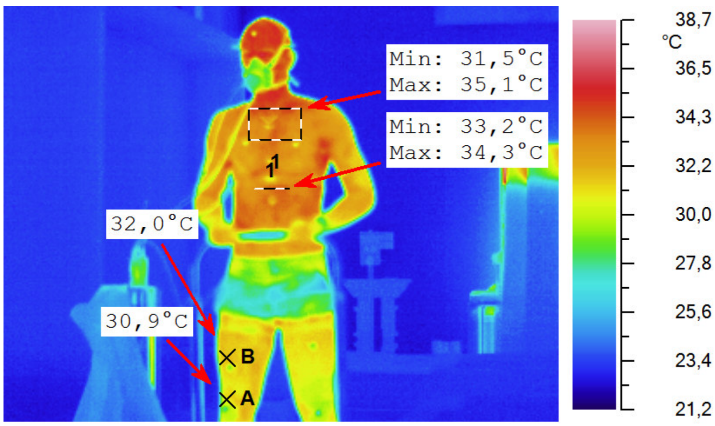
Tamb: 23C°

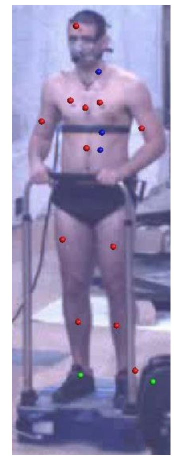
Histogram: thermal information about rectangle 1



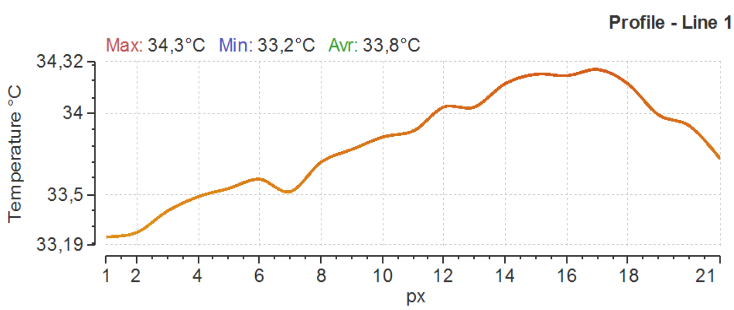
Subject 1	
Freq (vibr.tab)	20 Hz
No. jpg	IR_3400.jpg

Thermal Image | **Vision Image**





Curve showing temperatures of every line point



Temperature values at points

Point	T °C	Emis.	Ta °C
A	30,9°C	0,93	23,0
B	32,0°C	0,93	23,0

Working conditions

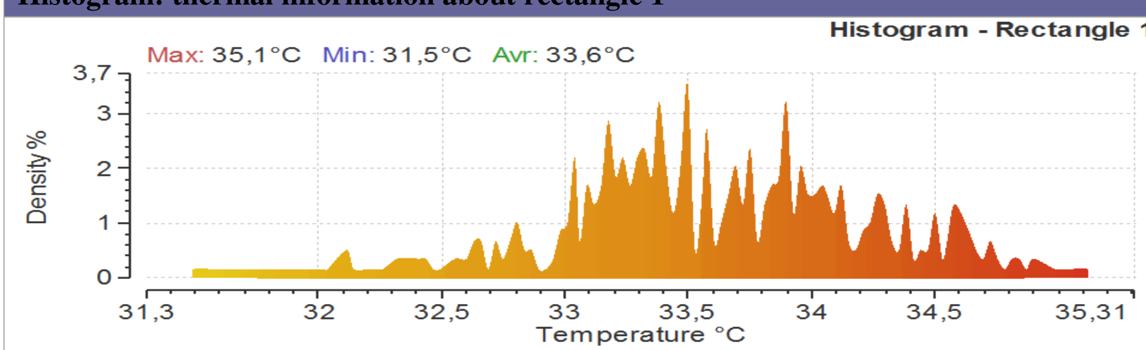
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

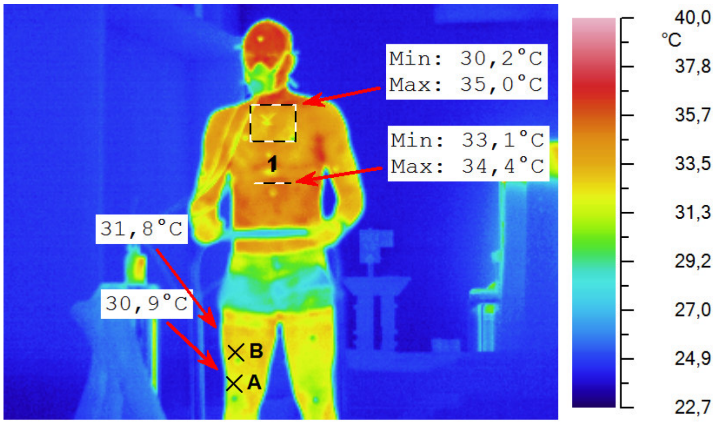
Tamb: 23C°

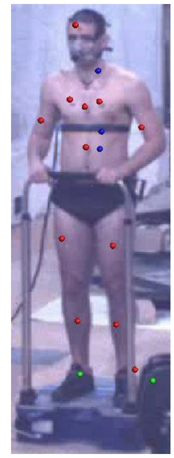
Histogram: thermal information about rectangle 1



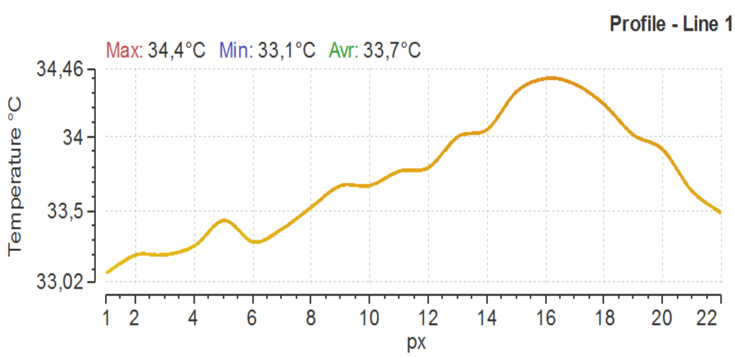
Subject 1	
Freq (vibr.tab)	20 Hz
No. jpg	IR_3414.jpg

Thermal Image	Vision Image





Curve showing temperatures of every line point



Temperature values at points

Point	T °C	Emis.	Ta °C
A	30,9°C	0,93	23,0
B	31,8°C	0,93	23,0

Working conditions

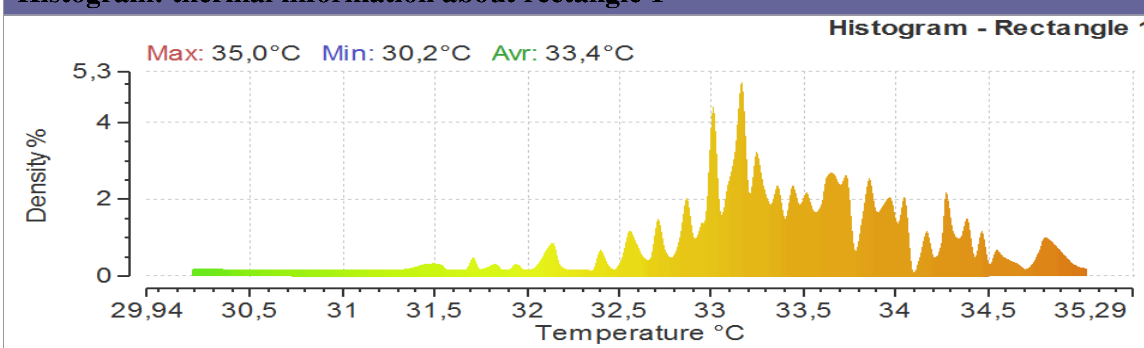
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

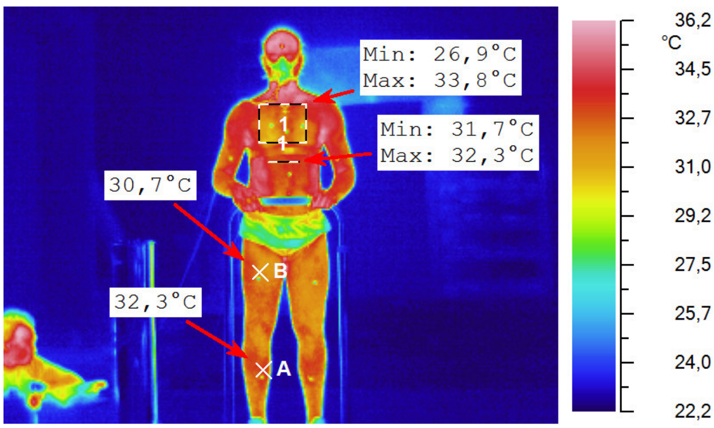
Tamb: 23C°

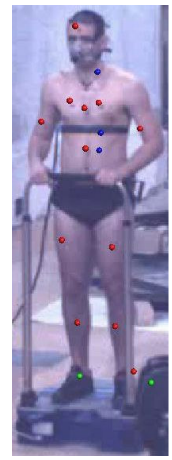
Histogram: thermal information about rectangle 1



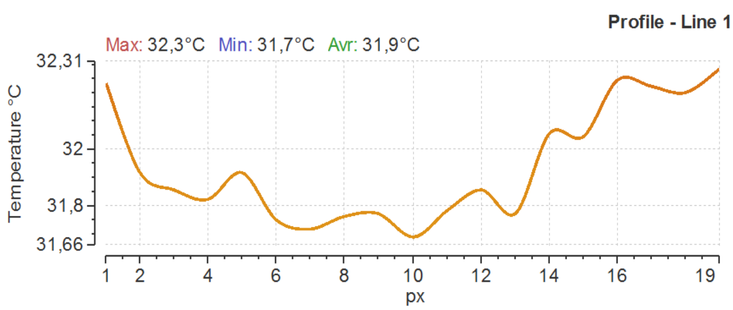
Subject 1	
Freq (vibr.tab)	30 Hz
No. jpg	IR_3418.jpg

Thermal Image **Vision Image**





Curve showing temperatures of every line point



Temperature values at points

Point	T °C	Emis.	Ta °C
A	32,3°C	0,93	23,0
B	30,7°C	0,93	23,0

Working conditions

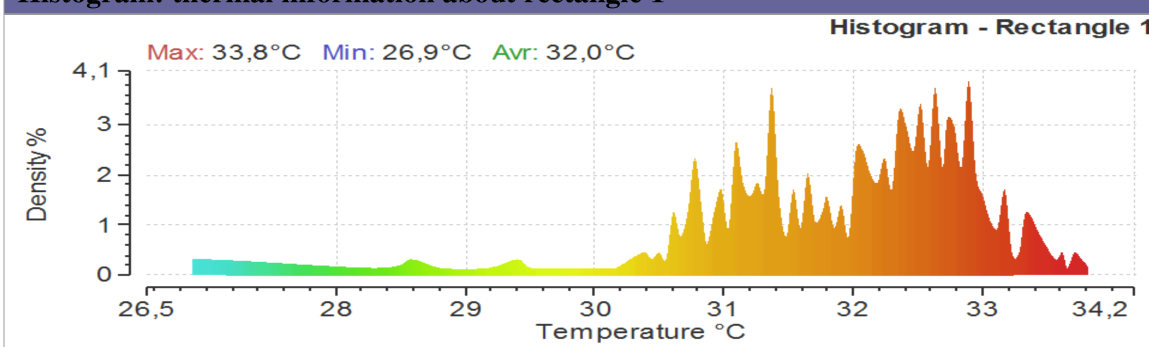
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

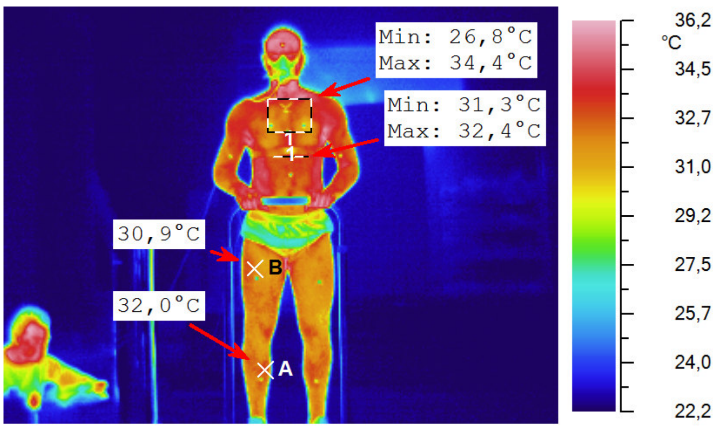
Tamb: 23C°

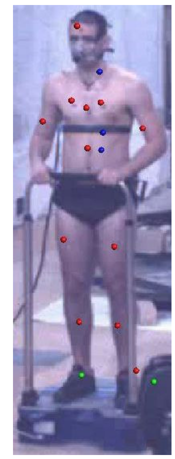
Histogram: thermal information about rectangle 1



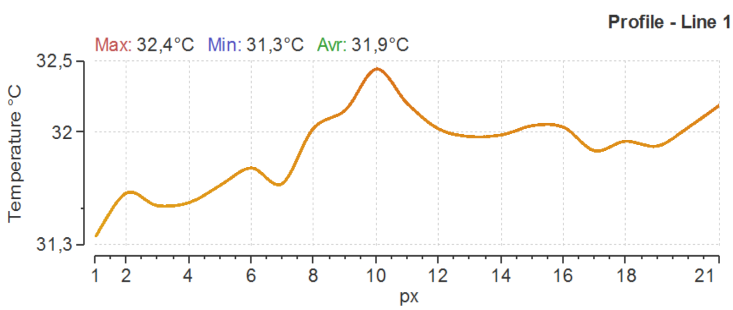
Subject 1	
Freq (vibr.tab)	30 Hz
No. jpg	IR_3427.jpg

Thermal Image	Vision Image





Curve showing temperatures of every line point



Temperature values at points

Point	T °C	Emis.	Ta °C
A	32,0°C	0,93	23,0
B	30,9°C	0,93	23,0

Working conditions

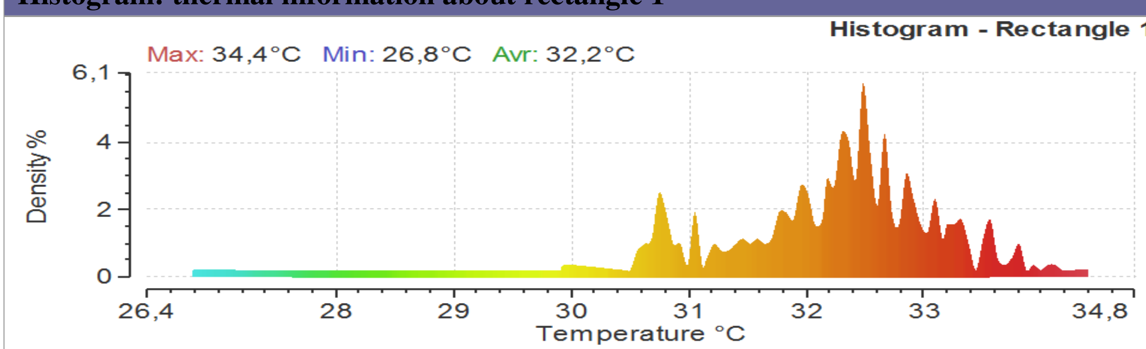
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

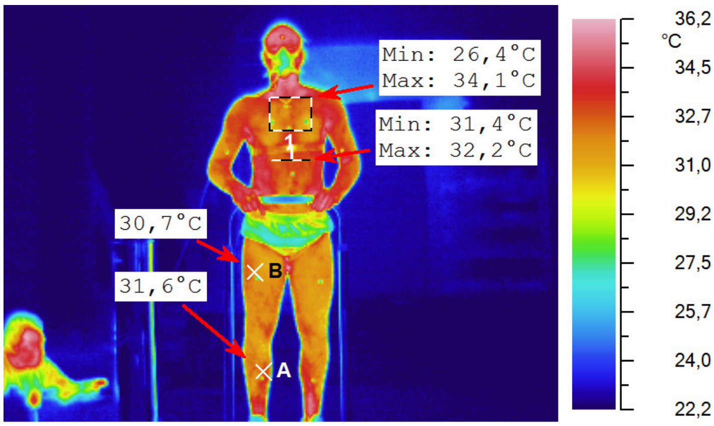
Tamb: 23C°

Histogram: thermal information about rectangle 1

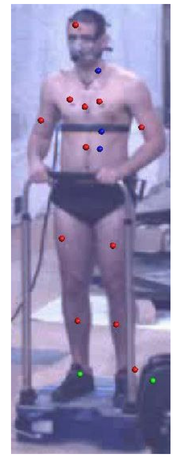


Subject 1	
Freq (vibr.tab)	30 Hz
No. jpg	IR_3452.jpg

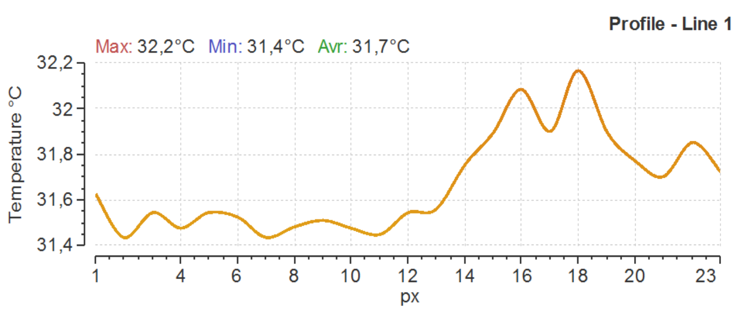
Thermal Image



Vision Image



Curve showing temperatures of every line point



Temperature values at points

Point	T °C	Emis.	Ta °C
A	31,6°C	0,93	23,0
B	30,7°C	0,93	23,0

Working conditions

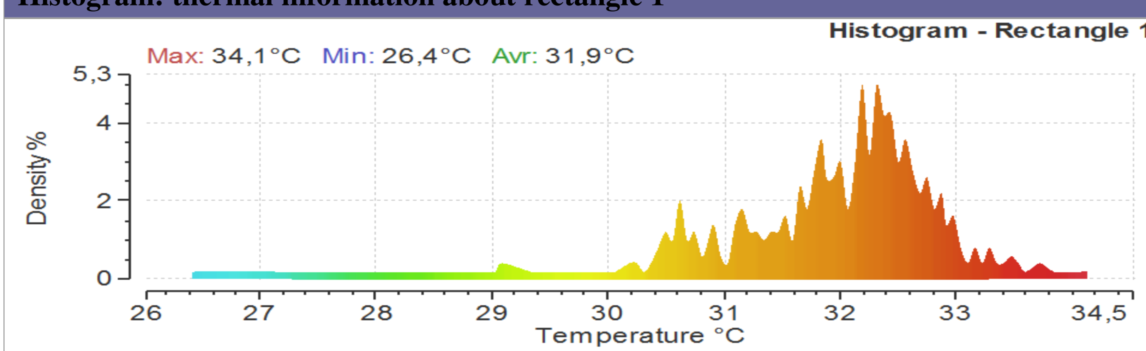
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

Tamb: 23C°

Histogram: thermal information about rectangle 1



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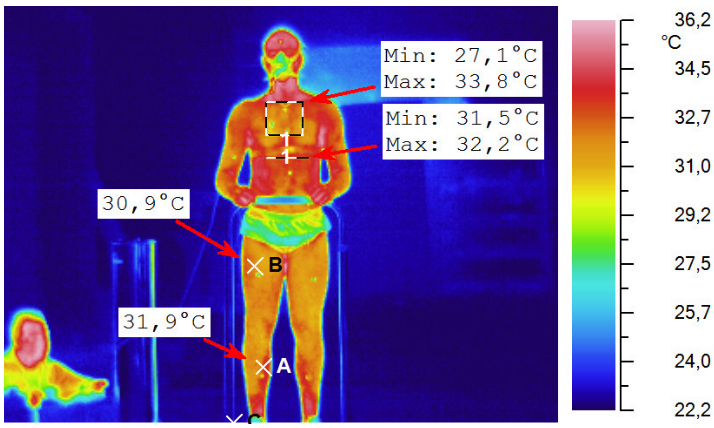
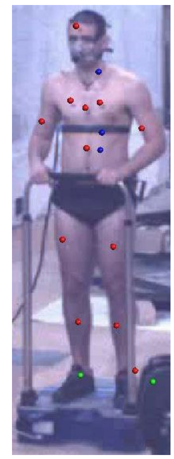
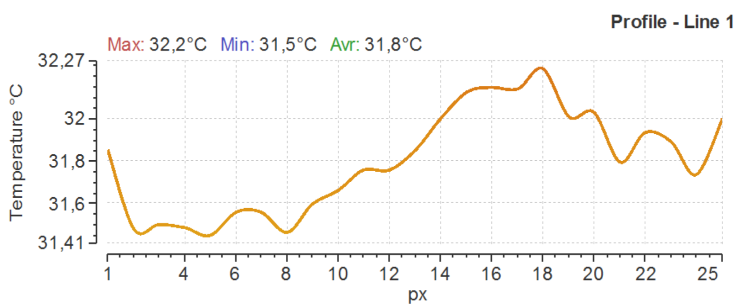
No. jpg	IR_3481.jpg

Thermal Image	Vision Image





Curve showing temperatures of every line point



Temperature values at points

Point	T °C	Emis.	Ta °C
A	31,9°C	0,93	23,0
B	30,9°C	0,93	23,0
C	23,4°C	0,93	1,5

Working conditions

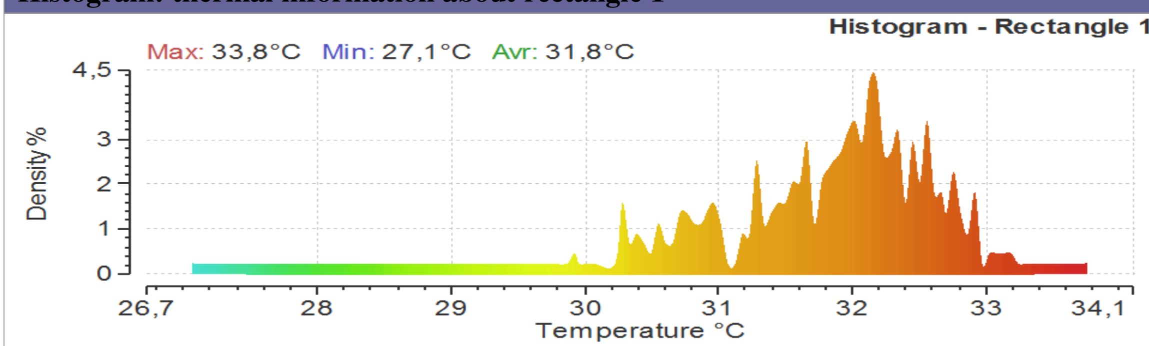
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

Tamb: 23C°

Histogram: thermal information about rectangle 1



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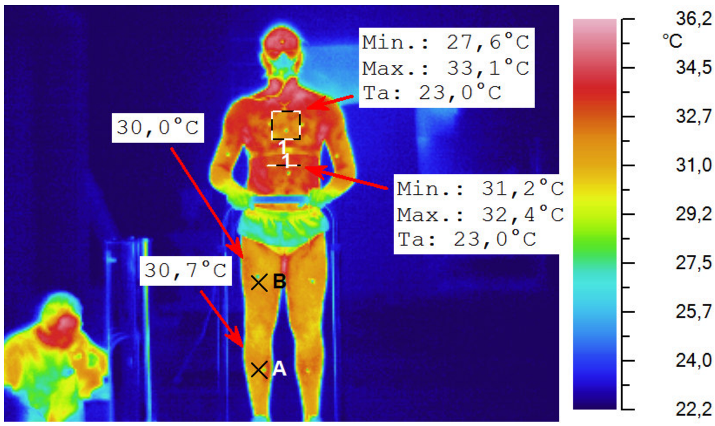
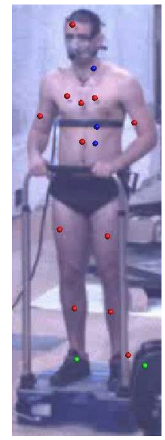
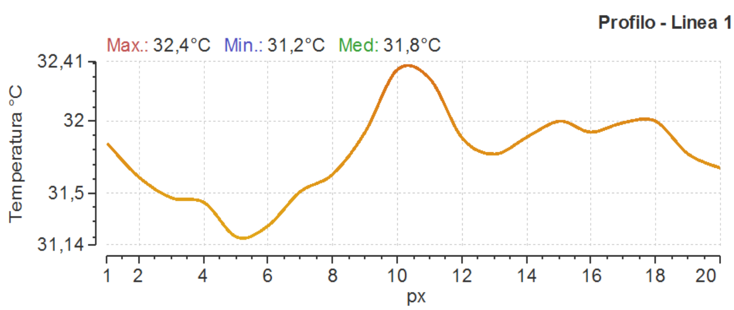
Freq (vibr.tab)	45 Hz
No. jpg	IR_3484.jpg

Thermal Image | **Vision Image**





Curve showing temperatures of every line point



Temperature values at points

Punto	T °C	Emis.	Ta °C
A	30,7°C	0,93	23,0
B	30,0°C	0,93	23,0

Working conditions

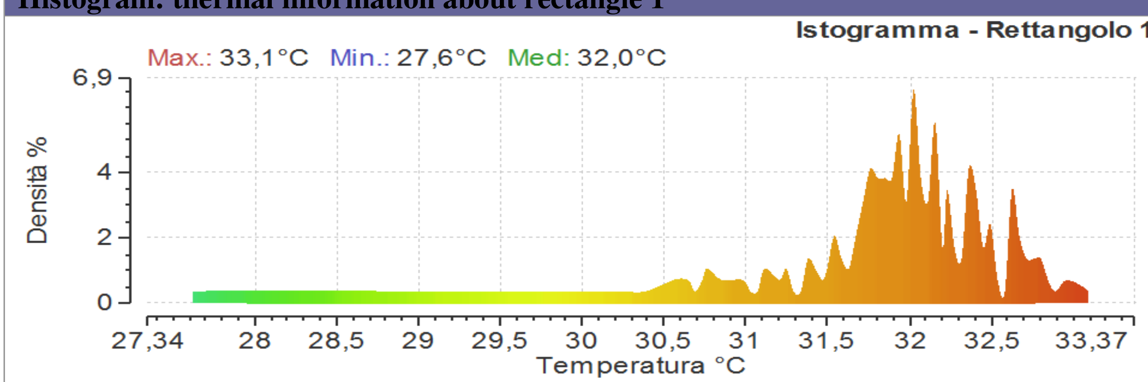
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

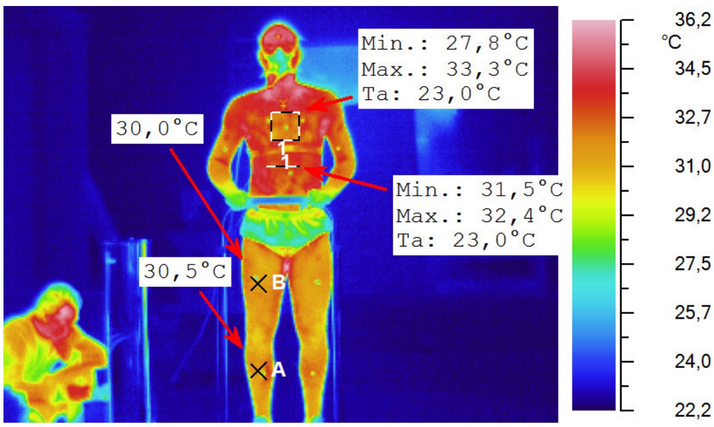
Tamb: 23C°

Histogram: thermal information about rectangle 1

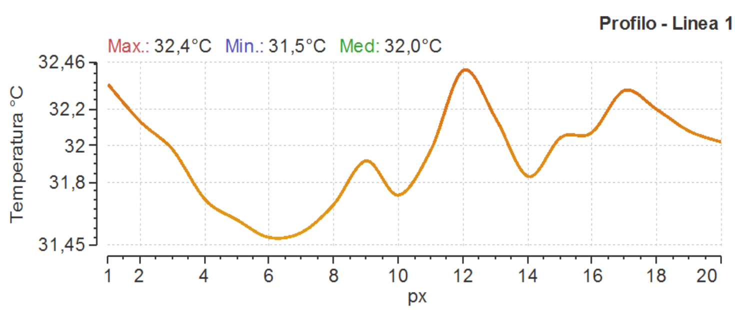


Subject 1	
Freq (vibr.tab)	45 Hz
No. jpg	IR_3494.jpg

Thermal Image | **Vision Image**



Curve showing temperatures of every line point



Temperature values at points

Punto	T °C	Emis.	Ta °C
A	30,5°C	0,93	23,0
B	30,0°C	0,93	23,0

Working conditions

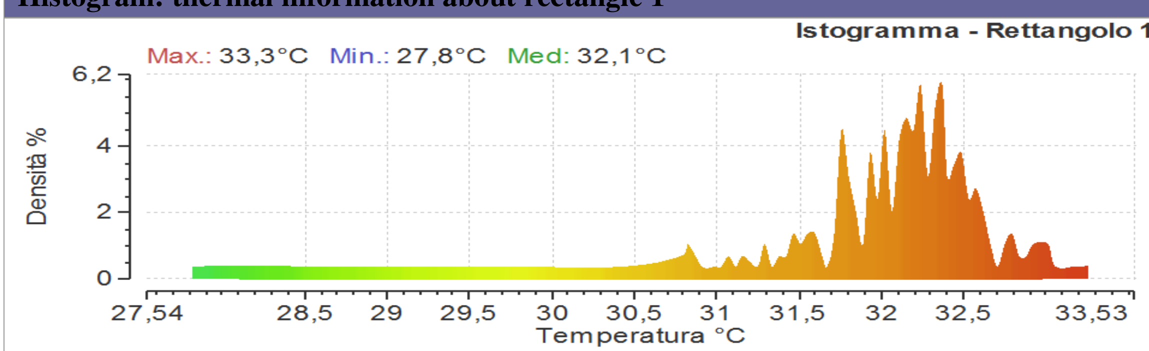
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

Tamb: 23C°

Histogram: thermal information about rectangle 1



Subject 1	
Freq (vibr.tab)	45 Hz
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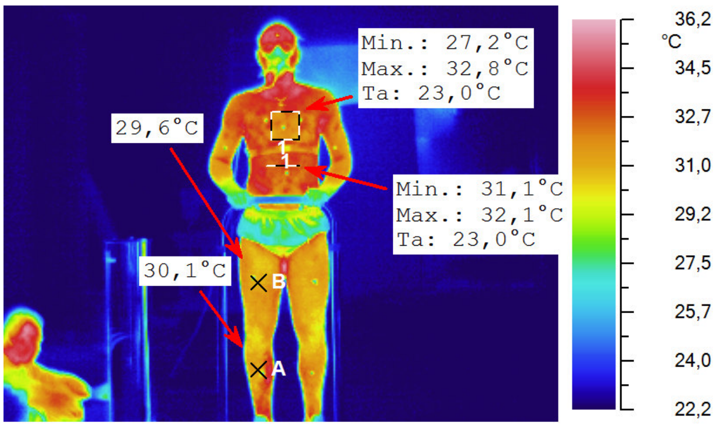
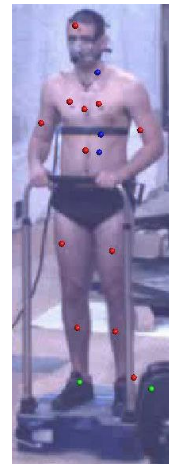
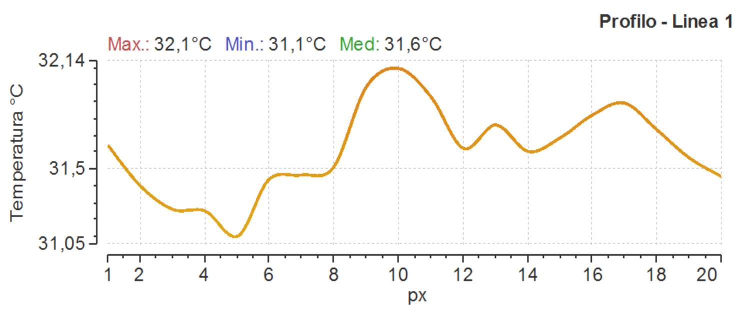
Thermal Image



Vision Image



Curve showing temperatures of every line point



Temperature values at points

Punto	T °C	Emis.	Ta °C
A	30,1°C	0,93	23,0
B	29,6°C	0,93	23,0

Working conditions

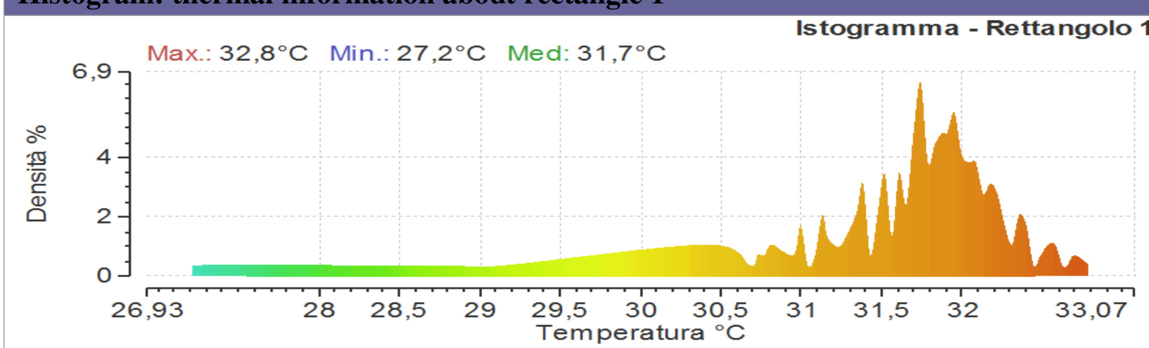
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

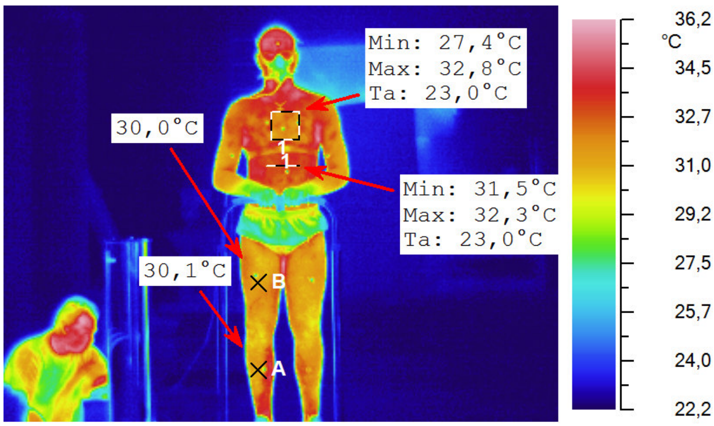
Tamb: 23C°lure

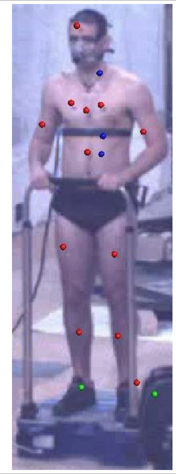
Histogram: thermal information about rectangle 1



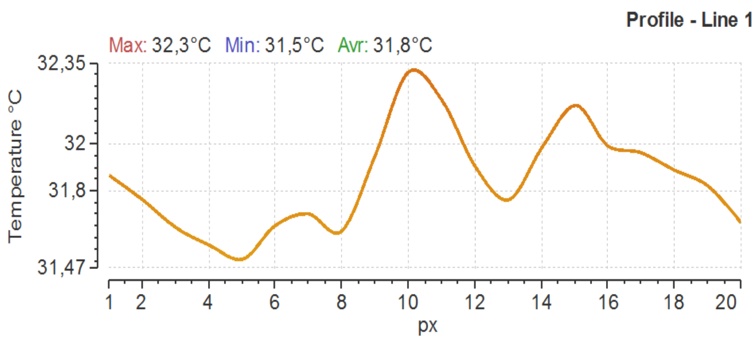
Subject 1	
Freq (vibr.tab)	45 Hz
No. jpg	3539

Thermal Image | **Vision Image**





Curve showing temperatures of every line point



Temperature values at points

Point	T °C	Emis.	Ta °C
A	30,1°C	0,93	23,0
B	30,0°C	0,93	23,0

Working conditions

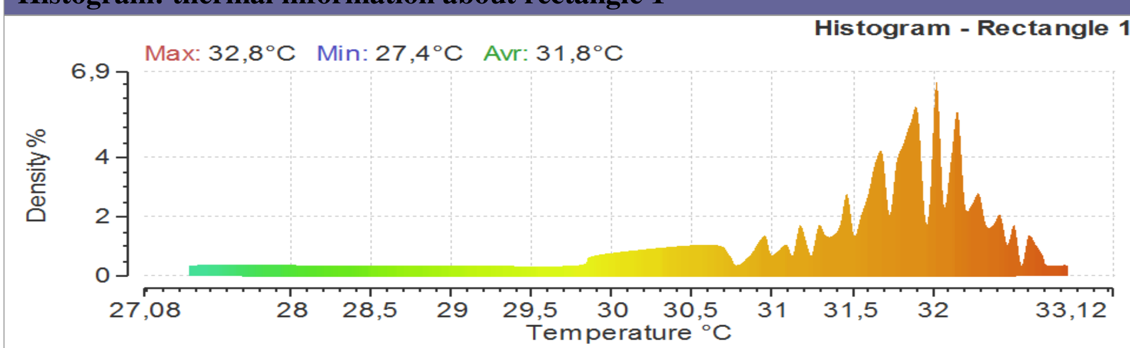
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

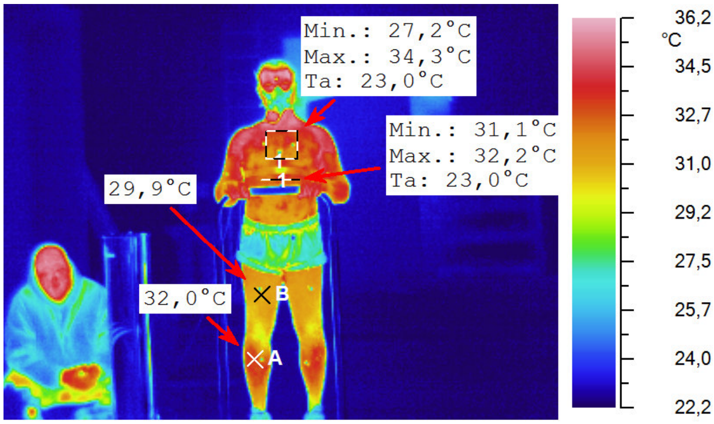
Tamb: 23C°

Histogram: thermal information about rectangle 1

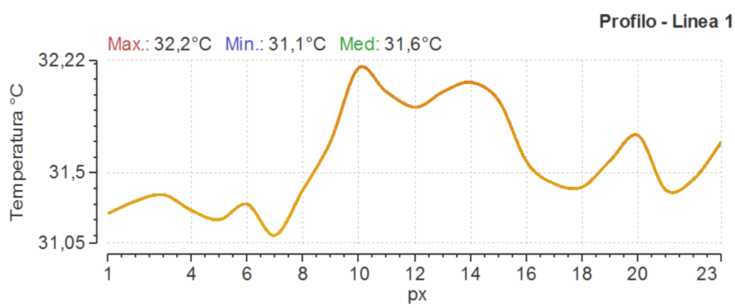


Subject 2	
Freq (vibr.tab)	20 Hz
No. jpg	IR_3541.jpg

Thermal Image	Vision Image



Curve showing temperatures of every line point



Temperature values at points

Punto	T °C	Emis.	Ta °C
A	32,0°C	0,93	23,0
B	29,9°C	0,93	23,0

Working conditions

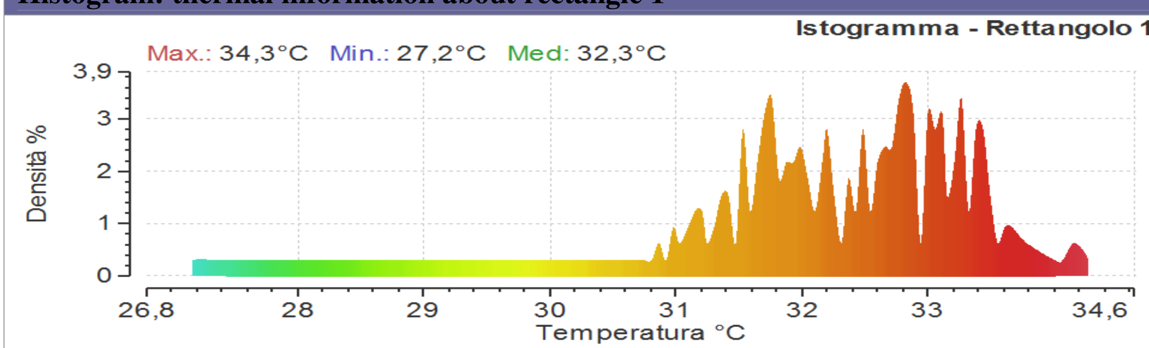
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

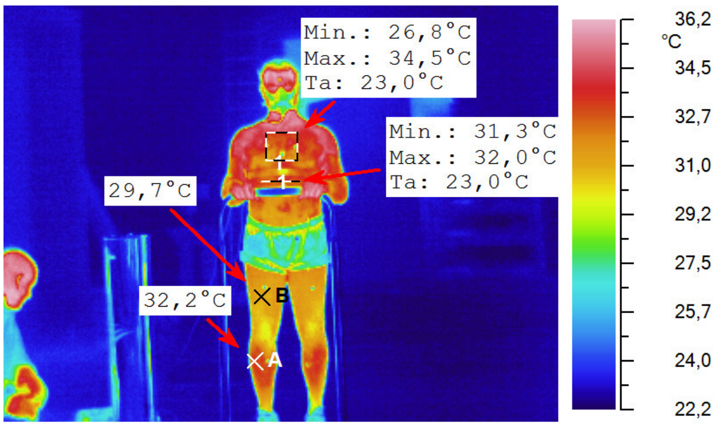
Tamb: 23C°

Histogram: thermal information about rectangle 1

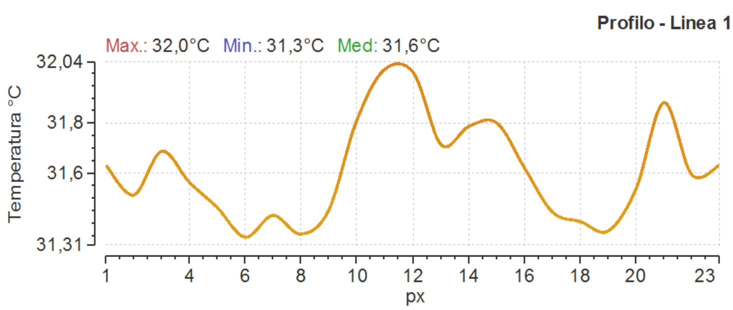


Subject 2	
Freq (vibr.tab)	20 Hz
No. jpg	IR_3550.jpg

Thermal Image **Vision Image**



Curve showing temperatures of every line point



Temperature values at points

Punto	T °C	Emis.	Ta °C
A	32,2°C	0,93	23,0
B	29,7°C	0,93	23,0

Working conditions

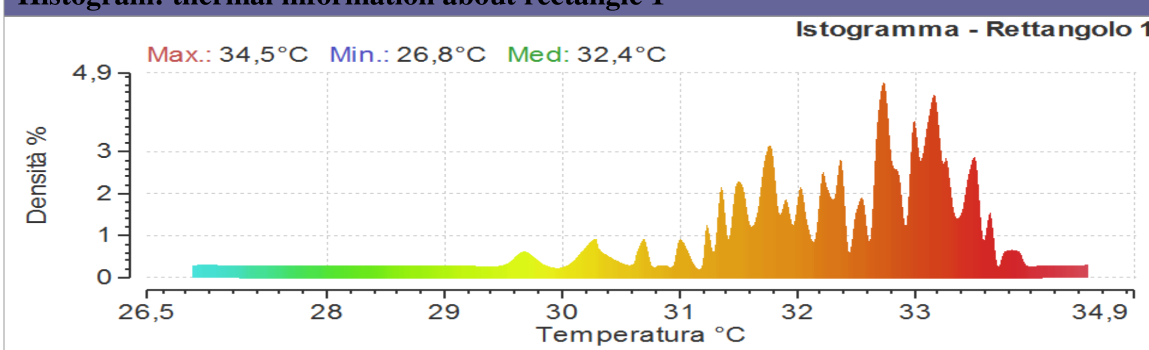
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

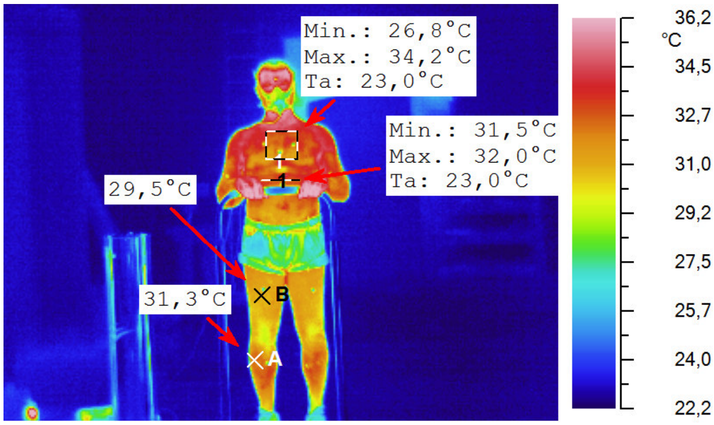
Tamb: 23C°

Histogram: thermal information about rectangle 1



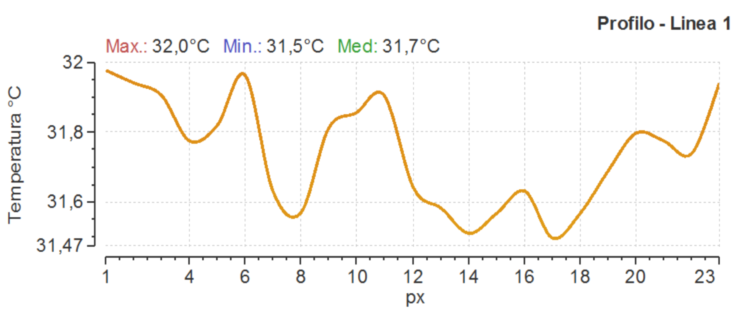
Subject 2	
Freq (vibr.tab)	20 Hz
No. jpg	IR_3575.jpg

Thermal Image



Vision Image

Curve showing temperatures of every line point



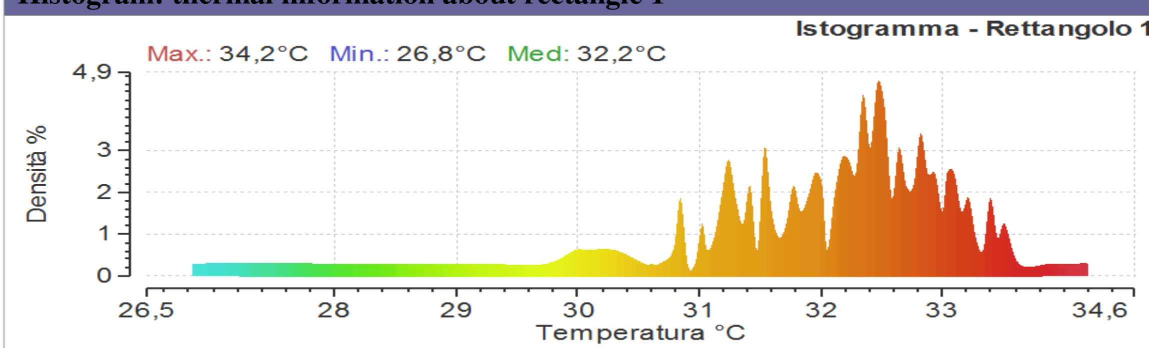
Temperature values at points

Punto	T °C	Emis.	Ta °C
A	31,3°C	0,93	23,0
B	29,5°C	0,93	23,0

Working conditions

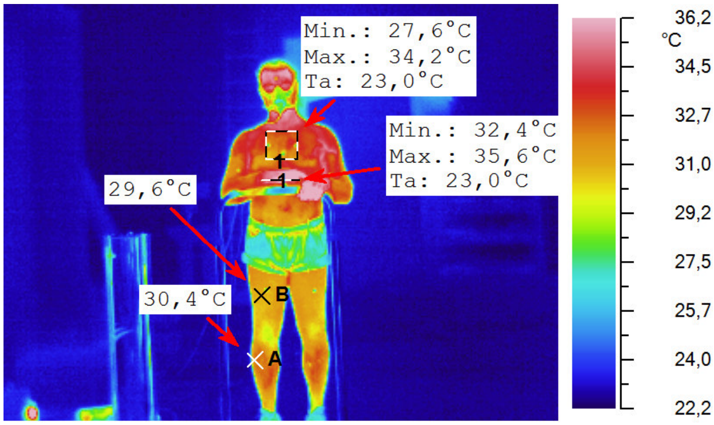
Range of thermography:
Tmax: 36C°, Tmin: 22C°
Humidity:
Tamb: 23C°

Histogram: thermal information about rectangle 1



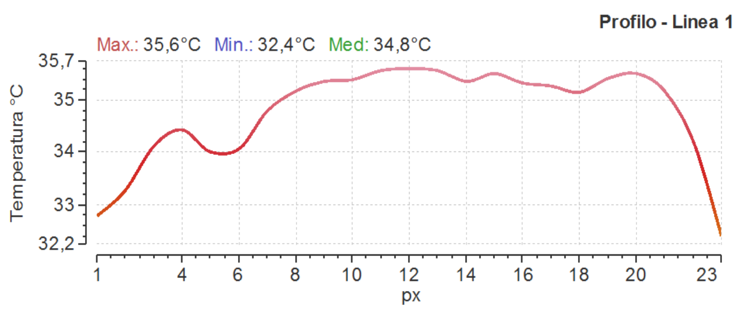
Subject 2	
Freq (vibr.tab)	20 Hz
No. jpg	IR_3596.jpg

Thermal Image



Vision Image

Curve showing temperatures of every line point



Temperature values at points

Punto	T °C	Emis.	Ta °C
A	30,4°C	0,93	23,0
B	29,6°C	0,93	23,0

Working conditions

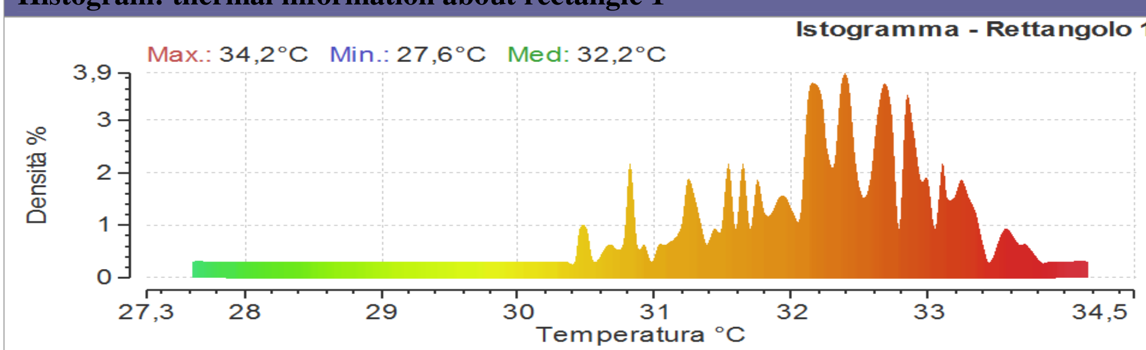
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

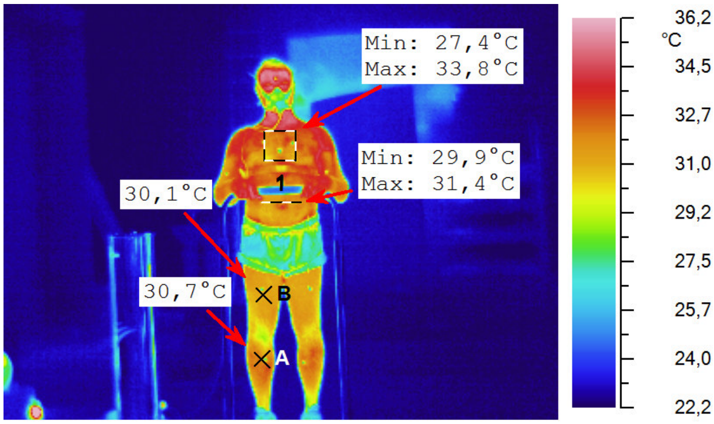
Tamb: 23C°

Histogram: thermal information about rectangle 1

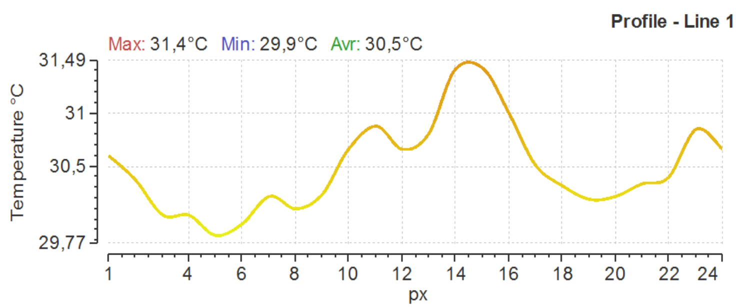


Subject 2	
Freq (vibr.tab)	45 Hz
No. jpg	3599

Thermal Image	Vision Image



Curve showing temperatures of every line point



Temperature values at points

Point	T °C	Emis.	Ta °C
A	30,7°C	0,93	23,0
B	30,1°C	0,93	23,0

Working conditions

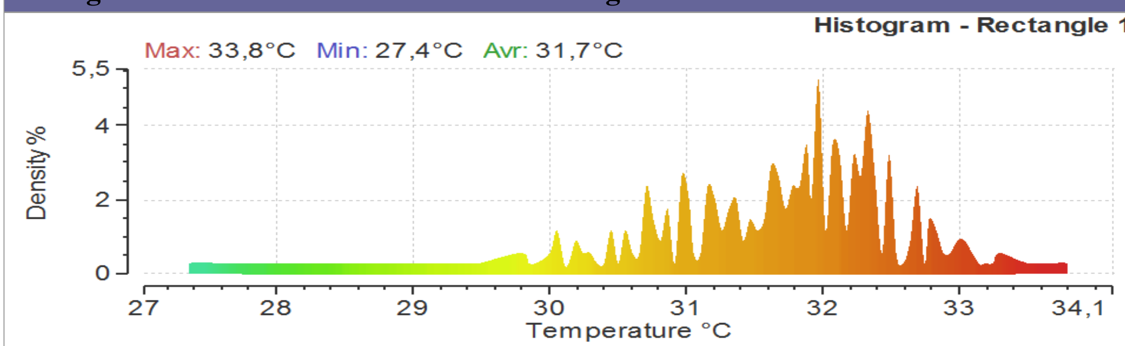
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

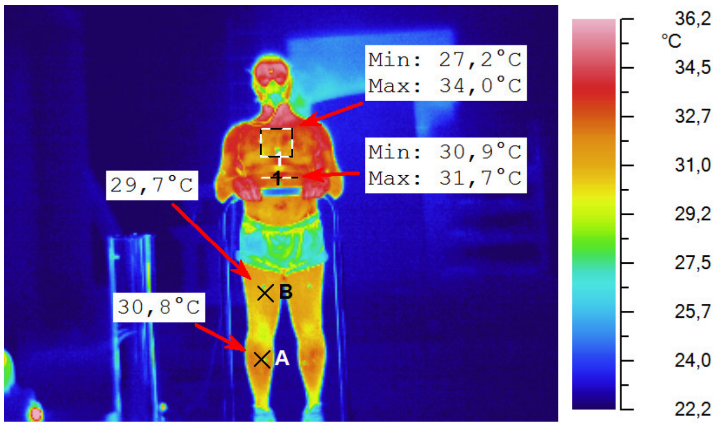
Tamb: 23C°re

Histogram: thermal information about rectangle 1

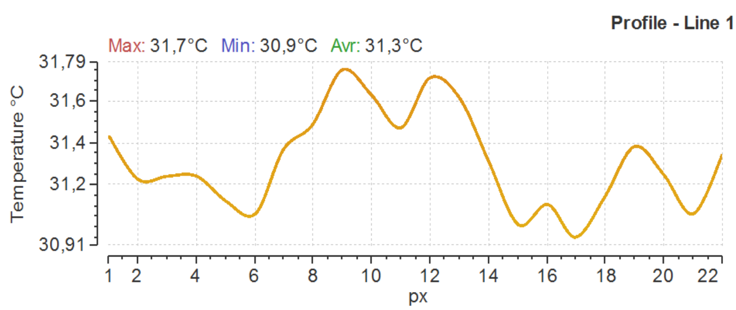


Subject 2	
Freq (vibr.tab)	45 Hz
No. jpg	IR_3607.jpg

Thermal Image | **Vision Image**



Curve showing temperatures of every line point



Temperature values at points

Point	T °C	Emis.	Ta °C
A	30,8°C	0,93	23,0
B	29,7°C	0,93	23,0

Working conditions

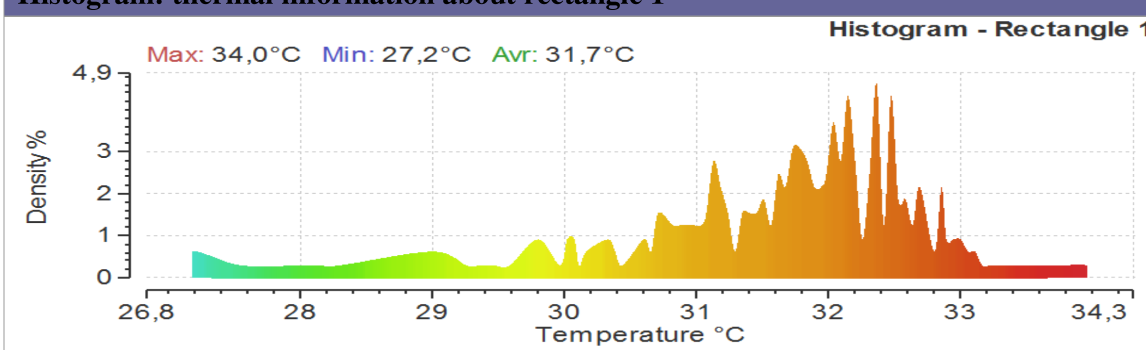
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

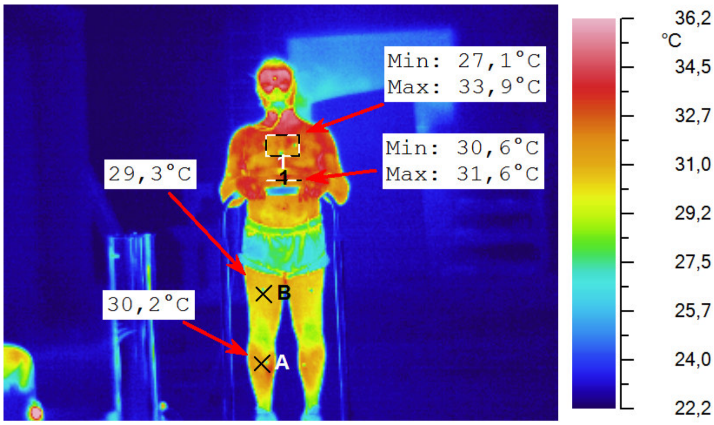
Tamb: 23C° Cla

Histogram: thermal information about rectangle 1

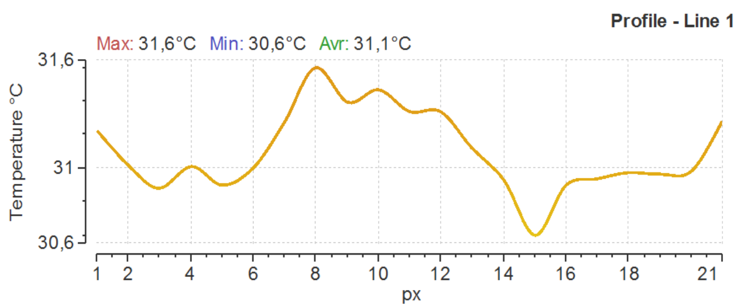


Subject 2	
Freq (vibr.tab)	45 Hz
No.img	IR_3632.jpg

Thermal Image | **Vision Image**



Curve showing temperatures of every line point



Temperature values at points

Point	T °C	Emis.	Ta °C
A	30,2°C	0,93	23,0
B	29,3°C	0,93	23,0

Working conditions

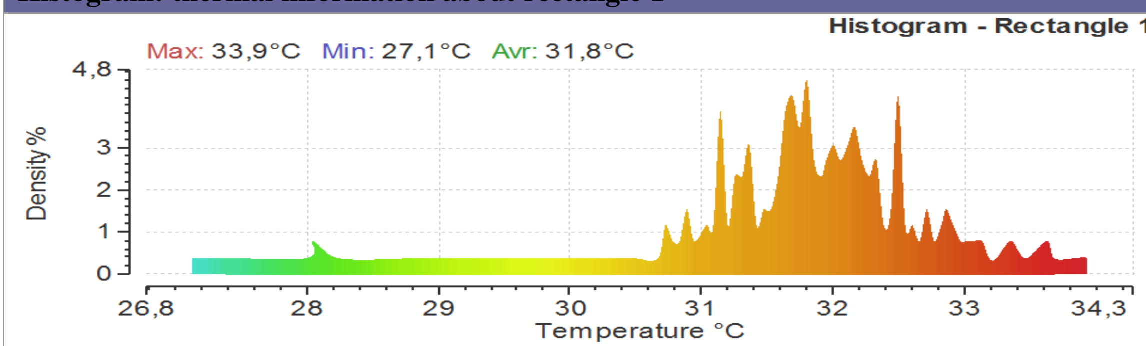
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

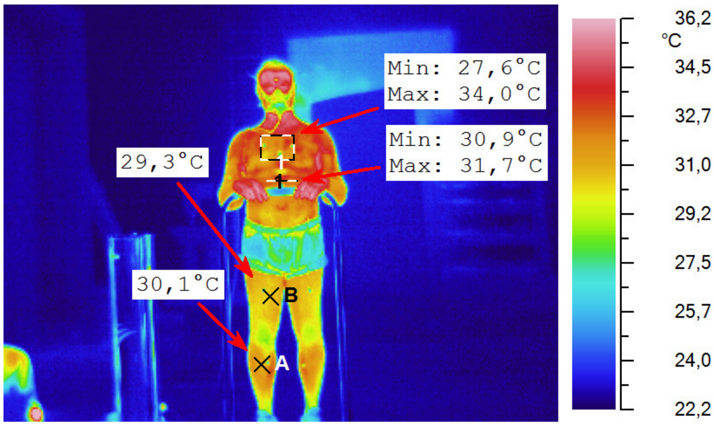
Tamb: 23C° Clas

Histogram: thermal information about rectangle 1

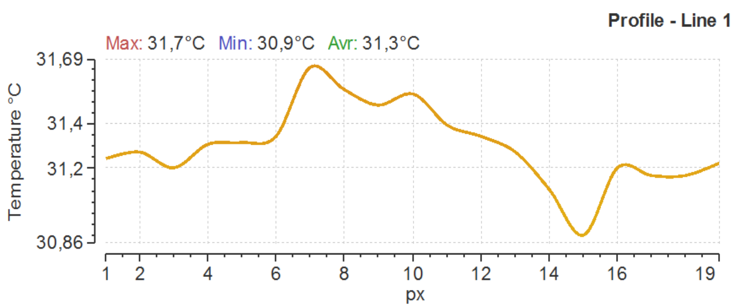


Subject 2	
Freq (vibr.tab)	45 Hz
No.img	IR_3652.jpg

Thermal Image	Vision Image



Curve showing temperatures of every line point



Temperature values at points

Point	T °C	Emis.	Ta °C
A	30,1°C	0,93	23,0
B	29,3°C	0,93	23,0

Working conditions

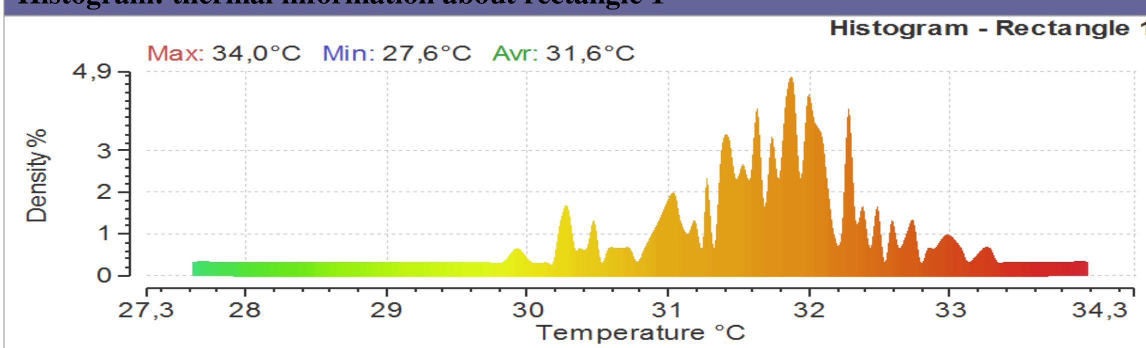
Range of thermography:

Tmax: 36C°, Tmin: 22C°

Humidity:

Tamb: 23C° C

Histogram: thermal information about rectangle 1



References – Chapter 12

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CHAPTER 13

Conclusions

In this chapter, a summary of the undertaken research is presented, along with the principal findings and suggestions for a future research of the whole-body vibration effects to the human body.

13.1 Research summary

The primary objective of this study was to develop and implement an appropriate whole-body vibration protocol and to study the effects of whole-body vibration to the human body in a standing position by means of energy expenditure.

Because of the complexity of the human body structure this problem could be better affronted by an integrated and global approach. For that reason, three different variables of the human body were accounted for: the oxygen uptake, the superficial temperature and the displacement of the muscles in a vibrating environment. Having information for these three variables, the effects of the whole-body vibration to the human body can be understand from a global point of view.

13.2 Findings

The most interesting findings in the case of the intermittent vibrations regard the oxygen consumption, the superficial temperature evolution, and the transmissibility and dispersion coefficients for the acceleration of the muscles.

First of all, a linear relationship between the frequency of vibration exposure and the average oxygen consumption is found with a good approximation.

Regarding the temperature evolution during the experiment, some interesting yet somewhat conflicting results are connected to the actual difference in superficial perfusion of the subjects. These results should be considered as an input for the follow-up of this research (see 13.3). At high frequency (45 Hz), in the first subject, there has been no significant variation, while in the second, the femur temperature has been diminished with the abdomen temperature more or less stable. At lower frequency (20 Hz), the abdomen temperature of the first subject decreases significantly, with the right and left femur increasing and decreasing respectively. The temperature of the second body (abdomen, left and right femur), presents a slight decrease.

Finally, the dispersion of the vibration from the vibrating table to the body and the transmissibility has been calculated. A number of interesting considerations can be made. It has been found that the percentage of vibration transmitted from the vibration table to the ankle, for a high vibration frequency (45 Hz), is strongly influenced by the subject and his morphological characteristics. In one case 37-39 % of the vibrations are transmitted while in the other 71-76 % (ratio 1 to 2). The transmissibility to the next body location (femur), is however inverted for the two subjects (9-12 % to 5-6 %). A further consideration for what concern the transmission of the vertical vibration from the vibrating table to the head was made. It has been asserted that, in both subjects, there is no dispersion of vertical vibrations from the vibrating table to the head. A partial transmissibility coefficient of the head almost equal to 1, with respect to the femur, was found for the two subjects. This should be related with the morphology (rigidity) of the head and the fact that there is no vertical dispersion through the bones, since the vibration is transmitted directly to the head through the vertebral column. On the other hand, the ankle joint and the knee joint play the important role of damping in vertical vibrations.

It has been found that the linear approximation cannot describe the effects of whole-body vibration in such kind of dynamic approach.

13.3 Future research

As stated several times, the human body is a complex organic structure, and in order to understand how it responds to vertical vibrations, it is useful to address the problem with an integrated and global approach.

In a future research, the concept of non-linear approximation should be introduced. This can be achieved by treating the human body as a structure composted by a number of complex anatomic structures which have a fractal-like behaviour.

It is well known that the evolution of the self organizing complex organic systems is described by their non linear evolution in time. If we observe at a microscopic and mesoscopic scale, with specific attention to the human body, we can find that all the inside physiological self organized complex structures such as the DNA, the coronary artery tree, the Purkinjie cells in cerebellum, the small intestine and others, exhibit the property of self-affinity, that is the natural form of the well known geometrical property of self similarity.

In general, all the self organizing complex systems, especially the biological ones, like the human body, are better described by non linear evolutions equations that are present in their static, kinematics and dynamics forms (fractals). The only connection among these different aspects is the generalized Brownian Motion in its every known formulation: classic, fractional, active and so on.

The surface temperature fluctuation of the human body is Brownian and it is appropriate to consider the specific heat c_v not as a constant but as a complicate function related to the time, the space, the food, the fat and the body dimensions. In reality, the human body is a complex engine with continuous production and dispersion of energy (the metabolic heat) that shows non linear evolution in many aspects. Another important consideration to take in the field of non linearity, for a future research, is that the pulmonary ventilation fluctuation and the muscle contraction are based on the Brownian motion [1, 2].

The non linearity approach is founded on the non linear self organized essence of the human body, and on the absence of linear relationships among our different data results in such “global” approach to the whole body vibration study, with specific attention to its dynamical evolution.

The introduction of the non-linearity in the study of whole-body vibration can be achieved by applying this research in a greater number of persons, in order to achieve statistical validation. This can be done by means of more experiments to different subject, classified in different classes in function of their physiological and biological characteristics (e.g. age, posture etc.).

Also, by introducing methods which take into consideration the non-linearity approximation such as the Sacripanti model which is already implemented in a LabView® simulation environment and it can be integrated with other methods for a global understanding of the human structure and its dynamics.

References – Chapter 13

[1] Sacripanti, A. Movement and Man at the end of the random walk. Int. Cong. Movement as prevention of health, University of Tor Vergata, Roma, 2006.

[2] Grimpampi, E., Pasculli A., Sacripanti A. Computational Biomechanics, Stochastic Motion and Team Sports. Proceedings of the Sixth International Conference on Engineering Computational Technology, Athens, 2008.

APPENDIX A

International Standards

A.1 International Standards

ISO/TC 108 MECHANICAL VIBRATION, SHOCK AND CONDITION MONITORING

ISO 1925:2001 Mechanical vibration - Balancing - Vocabulary.

ISO 1940-1:2003 Mechanical vibration - Balance quality requirements for rotors in a constant (rigid) state - Part 1: Specification and verification of balance tolerances.

ISO 1940-1:2003/COR. 1:2005 Technical Corrigendum 1 to ISO 1940-1:2003.

ISO 1940-2:1997 Mechanical vibration - Balance quality requirements of rigid rotors - Part 2: Balance errors.

ISO 2017-1:2005 Mechanical vibration and shock – Resilient mounting systems - Part 1: Technical information to be exchanged for the application of isolation systems.

ISO 2017-2:2007 Mechanical vibration and shock – Resilient mounting systems - Part 2: Technical information to be exchanged for the application of vibration isolation associated with railway systems.

ISO 2041:1990 Vibration and shock - Vocabulary.

ISO 2953:1999 Mechanical vibration - Balancing machines - Description and evaluation.

ISO 3719:1994 Mechanical vibration - Symbols for balancing machines and associated instrumentation.

ISO 4863:1984 Resilient shaft couplings - Information to be supplied by users and manufacturers.

ISO 7475:2002 Mechanical vibration - Balancing machines - Enclosures and other protective measures for the measuring station.

ISO 7626-1:1986 Vibration and shock - Experimental determination of mechanical mobility - Part 1: Basic definitions and transducers.

ISO 7626-2:1990 Vibration and shock - Experimental determination of mechanical mobility - Part 2: Measurements using single point translation excitation with an attached vibration exciter.

ISO 7626-5:1994 Vibration and shock - Experimental determination of mechanical mobility - Part 5: Measurements using impact excitation with an exciter which is not attached to the structure.

ISO 8821:1989 Mechanical vibration - Balancing - Shaft and fitment key convention.

ISO 9688:1990 Mechanical vibration and shock – Analytical methods of assessing shock resistance of mechanical systems – Information exchange between suppliers and users of analyses.

ISO 10112:1991 Damping materials - Graphical presentation of the complex modulus.

ISO 10814:1996 Mechanical vibration - Susceptibility and sensitivity of machines to unbalance.

ISO 11342:1998 Mechanical vibration - Methods and criteria for the mechanical balancing of flexible rotors. This Standard includes: ISO 11342/COR. 1:2000 Technical Corrigendum 1 to ISO 11342:1998.

ISO 16587:2004 Mechanical vibration and shock – Performance parameters for condition monitoring of structures.

ISO 18431-1:2005 Mechanical vibration and shock – Signal processing - Part 1: General introduction.

ISO 18431-2:2004 Mechanical vibration and shock – Signal processing – Part 2: Time domain windows for Fourier Transform analysis.

ISO 18431-2:2004/COR. 1:2008 Technical Corrigendum 1 to ISO 18431-2:2004.

ISO 18431-4:2007 Mechanical vibration and shock – Signal processing – Part 4: Shockresponse spectrum analysis.

ISO 18437-2:2005 Mechanical vibration and shock – Characterization of the dynamic mechanical properties of visco-elastic materials – Part 2: Resonance method.

ISO 18437-3:2005 Mechanical vibration and shock – Characterization of the dynamic mechanical properties of visco-elastic materials – Part 3: Cantilever shear beam method.

ISO 18437-4:2008 Mechanical vibration and shock – Characterization of the dynamic mechanical properties of visco-elastic materials – Part 4: Dynamic stiffness method.

ISO 19499:2007 Mechanical vibration – Balancing – Guidance on the use and application of balancing standards.

ISO 20806:2004 Mechanical vibration – Criteria and safeguards for the in-situ balancing of medium and large rotors.

ISO 21289:2008 Mechanical vibration and shock – Parameters to be specified for the acquisition of vibration data.

ISO/TC 108/SC4 HUMAN EXPOSURE TO MECHANICAL VIBRATION AND SHOCK

ISO 2631-1:1997 Mechanical vibration and shock – Evaluation of human exposure to whole body vibration - Part 1: General requirements.

ISO 2631-2:2003 Mechanical vibration and shock - Evaluation of human exposure to whole body

vibration - Part 2: Vibration in buildings (1 Hz to 80 Hz).

ISO 2631-4:2001 Mechanical vibration and shock – Evaluation of human exposure to whole body

vibration - Part 4: Guidelines for the evaluation of the effects of vibration and rotational motion on passenger and crew comfort in fixed-guide way transport systems.

ISO 2631-5:2004 Mechanical vibration and shock – Evaluation of human exposure to whole body

vibration - Part 5: Method for evaluation of vibration containing multiple shocks.

ISO 5349-1:2001 Mechanical vibration - Measurement and evaluation of human exposure to hand-transmitted vibration - Part 1: General requirements.

ISO 5349-2:2001 Mechanical vibration - Measurement and evaluation of human exposure to hand-transmitted vibration - Part 2: Practical guidance for measurement at the workplace.

ISO 5805:1997 Mechanical vibration and shock – Human exposure - Vocabulary.

ISO 5982:2001 Mechanical vibration and shock - Range of idealized values to characterize seated-body biodynamic response under vertical vibration.

ISO 6897:1984 Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and offshore structures, to low-frequency horizontal motion (0,063 to 1 Hz).

ISO 8727:1997 Mechanical vibration and shock – Human exposure – Biodynamic coordinate systems.

ISO 9996:1996 Mechanical vibration and shock – Disturbance to human activity and performance - Classification.

ISO 10068:1998 Mechanical vibration and shock - Free, mechanical impedance of the human hand-arm system at the driving point.

ISO 10227:1996 Human/human surrogate impact (single shock) testing and evaluation - Guidance on technical aspects.

ISO 10326-1:1992 Mechanical vibration - Laboratory method for evaluating vehicle seat vibration - Part 1: Basic requirements.

ISO 10326-1:1992/AMD 1:2007 Amendment 1 to ISO 10326-1:1992.

ISO 10326-2:2001 Mechanical vibration - Laboratory method for evaluating vehicle seat vibration - Part 2: Application to railway vehicles.

ISO 10819:1996 Mechanical vibration and shock - Hand-arm vibration - Method for the measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand.

ISO 13090-1:1998 Mechanical vibration and shock – Guidance on safety aspects of tests and experiments with people – Part 1: Exposure to whole-body mechanical vibration and repeated shock.

ISO 13091-1:2001 Mechanical vibration - Vibrotactile perception thresholds for the assessment of nerve dysfunction - Part 1: Methods of measurement at the fingertips.

ISO 13091-2:2003 Mechanical vibration - Vibrotactile perception thresholds for the assessment of nerve dysfunction - Part 2: Analysis and interpretation of measurements at the fingertips.

ISO 13753:1998 Mechanical vibration and shock - Hand-arm vibration - Method for measuring the vibration transmissibility of resilient materials when loaded by the hand-arm system.

ISO 14835-1:2005 Mechanical vibration and shock – Cold provocation tests for the assessment of peripheral vascular function – Part 1: Measurement and evaluation of finger skin temperature.

A.2 American Standards

ANSI S2.1-2000 / ISO 2041:1990 American National Standard Vibration and Shock - Vocabulary.

(Nationally Adopted International Standard).

ANSI S2.2-1959 (R 2006) American National Standard Methods for the Calibration of Shock and

Vibration Pickups.

ANSI S2.4-1976 (R 2004) American National Standard Method for Specifying the Characteristics of Auxiliary Analog Equipment for Shock and Vibration Measurements.

ANSI S2.7-1982 (R 2004) American National Standard Balancing Terminology.

ANSI S2.8-2007 American National Standard Technical Information Used for Resilient Mounting Applications.

ANSI/ASA S2.9-2008 American National Standard Parameters for Specifying Damping Properties of Materials and System Damping.

ANSI S2.16-1997 (R 2006) American National Standard Vibratory Noise Measurements and Acceptance Criteria of Shipboard Equipment.

ANSI S2.17-1980 (R 2004) American National Standard Techniques of Machinery Vibration Measurement.

ANSI S2.19-1999 (R 2004) American National Standard Mechanical Vibration—Balance Quality Requirements of Rigid Rotors, Part 1: Determination of Permissible Residual Unbalance, Including Marine Applications.

ANSI S2.20-1983 (R 2006) American National Standard Estimating Air Blast Characteristics for Single Point Explosions in Air, with a Guide to Evaluation of Atmospheric Propagation and Effects.

ANSI S2.21-1998 (R 2007) American National Standard Method for Preparation of a Standard Material for Dynamic Mechanical Measurements.

ANSI S2.22-1998 (R 2007) American National Standard Resonance Method for Measuring the Dynamic Mechanical Properties of Viscoelastic Materials.

ANSI S2.23-1998 (R 2007) American National Standard Single Cantilever Beam Method for Measuring the Dynamic Mechanical Properties of Viscoelastic Materials.

ANSI S2.24-2001 (R 2006) American National Standard Graphical Presentation of the Complex Modulus of Viscoelastic Materials.

ANSI S2.25-2004 American National Standard Guide for the Measurement, Reporting, and Evaluation of Hull and Superstructure Vibration in Ships.

ANSI S2.26-2001 (R 2006) American National Standard Vibration Testing Requirements and Acceptance Criteria for Shipboard Equipment.

ANSI S2.27-2002 (R 2007) American National Standard Guidelines for the Measurement and Evaluation of Vibration of Ship Propulsion Machinery.

ANSI S2.28-2003 American National Standard Guide for the Measurement and Evaluation of Vibration of Shipboard Machinery.

ANSI S2.29-2003 American National Standard Guide for the Measurement and Evaluation of Vibration of Machine Shafts on Shipboard Machinery.

ANSI S2.31-1979 (R 2004) American National Standard Methods for the Experimental Determination of Mechanical Mobility, Part 1: Basic Definitions and Transducers.

ANSI S2.32-1982 (R 2004) American National Standard Methods for the Experimental Determination of Mechanical Mobility, Part 2: Measurements Using Single-Point Translational Excitation.

ANSI S2.34-1984 (R 2005) American National Standard Guide to the Experimental Determination of Rotational Mobility Properties and the Complete Mobility Matrix.

ANSI S2.42-1982 (R 2004) American National Standard Procedures for Balancing Flexible Rotors.

ANSI S2.43-1984 (R 2005) American National Standard Criteria for Evaluating Flexible Rotor Balance.

ANSI S2.46-1989 (R 2005) American National Standard Characteristics to be Specified for Seismic
Transducers.

ANSI S2.48-1993 (R 2006) American National Standard Servo-Hydraulic Test Equipment for Generating Vibration - Methods of Describing Characteristics.

ANSI S2.60-1987 (R 2005) American National Standard Balancing Machines - Enclosures and Other Safety Measures.

ANSI S2.61-1989 (R 2005) American National Standard Guide to the Mechanical Mounting of Accelerometers.

ANSI S2.70-2006 American National Standard Guide for the Measurement and Evaluation of Human Exposure to Vibration Transmitted to the Hand.

ANSI S2.71-1983 (R 2006) American National Standard Guide to the Evaluation of Human Exposure to Vibration in Buildings (Reaffirmation and redesignation of ANSI S3.29-1983).

ANSI S2.72/Part 1-2002 (R 2007)/ISO 2631-1:1997 (Redesignation of ANSI S3.18/Part 1-2002 /
ISO 2631-1:1997) American National Standard Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration – Part 1: General requirements. (Nationally Adopted International Standard).

ANSI S2.72/Part 4-2003 (R 2007)/ISO 2631-4:2001 (Redesignation of ANSI S3.18/Part 4 - 2003/ISO 2631-4:2001) American National Standard Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration – Part 4: Guidelines for the evaluation of the effects of vibration and rotational motion on passenger and crew comfort in fixed-guideway transport systems. (Nationally Adopted International Standard).

ANSI S2.73-2002/ISO 10819:1996 (R 2007) (Redesignation of ANSI S3.40-2002/ISO 10819:1996) American National Standard Mechanical vibration and shock - Hand-arm vibration - Method for the measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand. (Nationally Adopted International Standard).