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Breathing training characterization by thermal imaging: a case study

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Specific respiratory muscle training improves athletes' performance particularly at high intensities. This work aims to study the usability of infrared thermography to evaluate two types of breathing, thoracic and diaphragmatic, on the cartographies of the cutaneous temperature of the trunk. IR thermography is a non-invasive technique that visually represents the whole process during and after training. A well trained subject in both respirations performed the exercise with SpiroTiger® for 5 minutes, followed by 5 minutes of recovery. Ten Regions of Interest on the subject skin were selected following anatomical and functional correspondence with the muscles involved in breathing. In order to check functional behaviour of respiratory muscles, we calculated the correlation among thermal data of all the ROI. Global temperature of body trunk showed a general decrease of few degrees during both kinds of the training but thermal imaging documented also thermal spots of increasing temperature in pectoral areas due to the superficial vasocirculation in thoracic breathing. The results indicate that thermal imaging can be used for quantitative evaluation of the cutaneous temperature in various trunk zones characterized by thoracic and diaphragmatic breathing. This work can be considered a preliminary study to the development of future statistical study.

Key words: *thermography, thermoregulation, respiratory muscles, skin temperature*

1. Introduction

An increasing number of clinical studies [3], [6], [13]–[15] show that a specific respiratory muscle training improves athletes' performance particularly at high intensities as it is limited by the activity of the respiratory system [7]. In fact, up to 15% of the total energy spent in high-intensity exercise is designed for the respiratory system reducing the amount of blood sent to other muscles [7]; therefore, the effect of reducing the work of breathing during the high-intensity exercise would improve the endurance capacity of athletes [7].

IR thermography represents the best approach to put in evidence all the skin temperature differences between the two kinds of breathing due to noninvasiveness and remote control. In such thermography experiments, in fact, skin is free of probes and thermoregulation is not prevented [12]. Skin temperature measurements present some limitations due to perspiration and to convection exchange, that has strong relationship for instance with the wind speed. Both effects have been reduced in our experimental setup. The activation of body compensatory vasoregulation occurs during the activity of the respiratory muscles, like in other muscles activities, through reduction of blood flow in the splanchnic region and tegumentary apparatus. Intense exercise causes heat production in the core structures and activates muscles, with a consequent massive transfer of warmer blood from the internal to the superficial parts of

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the body. In the muscular areas blood flow increases while blood volume remains constant due to the vasoconstriction in these regions. The blood volume in the internal and in the periferical parts of the body decreases. In this condition we can observe an increase of the venous return and the cardiac output [12].

In this work, we considered two different dynamics of breathing, generally called thoracic and diaphragmatic. In thoracic breathing, the muscles mainly involved in the *inspiration phase* are those that lift the rib cage: the external intercostal muscles, the accessory inspiratory muscles attached to the shoulder-humerus girdle and to the cervical part of the spine. In the *expiratory phase*, the muscles that constrict and lower the rib cage are: the rectus abdominis, the obliques, the quadratus lumborum and the internal intercostals. The above mentioned muscles are all superficial muscles of the front and rear side of the trunk. The diaphragm operates in a marginal way [4].

In diaphragmatic breathing [1], [10], the diaphragm carries out its physiological role as the main inspiratory muscle. Positioned inside the rib cage, it is barely detectable from the outside. The expiratory phase is instead carried out mainly by the elastic recoil of the diaphragm in its relaxed position (first passive phase of exhalation), by the expiratory muscles exercising abdominal pressure in the lateral wall of the abdomen (the oblique), by the posterior muscles of the thoracic-lumbar spine, by the quadratus lumborum, by the internal intercostals (the second phase of forced expiration). The rib cage remains in its expanded position, almost still, without participating in the movement of expansion and shrinkage thereof. The diaphragm's movement as it moves down and back up, as in the movement of a piston in a cylinder, [10] is directly responsible for the expansion and shrinkage of the rib cage in its vertical direction.

Under controlled laboratory conditions and with a well trained subject, an evaluation of the respiratory muscle training can be obtained by the use of IR thermography. It is the best technique for this aim due to its skill in representing by images the whole process with high thermal resolution [9]. In respiratory muscle training there are different rates of heat exchange between human body and the surrounding environment. In fact, many different parts of the human body are naturally designed for heat excess dissipation by convection, evaporation or irradiation during intense physical load [9]. Heat dissipation is influenced by different variables: body surface, presence of body hair on the skin and fat distribution. These variables are different between male and female: in particular, fat distribution is influenced by hormonal regulation. To limit these variables a male subject was chosen in this case study. For breathing exercise in laboratory conditions there was no significant movement of the subject in the surrounding air, the predominant heat exchange is evaporation and dissipative radiation being the second reduced by the effectiveness of the first one [8].

MERLA et al. [12] studied thermoregulation during and after the exercise in runners as well as TORII et al. [16] in cyclists with IR thermography. Both found characteristic trends concerning temperature. Only few papers [2], [18] are addressed to the evaluation of contribution of different body areas to specific physical exercise. Some differences of heating for different zones were found by ZAIDI et al. [17], but in different parts of the body (e.g., in swimmers).

This work represents a novel study due to scarcity of scientific literature on this subject.

2. Materials and methods

The subject taking part in this study is a skin diver, trained to practice both types of respiration, in fact he also uses regularly SpiroTiger® (Medical, Idiag AG, Fehraltorf, Switzerland) in his training sessions. The athlete has good morphological characteristics (BMI = 23.6) to permit ideal conditions for what concerns thermographic shooting (i.e., no body hair, low subcutaneous fat). A bioelectrical impedance analyzer (BC-418-MA, Tanita, Japan) was used to analyze body composition. We also measured pectoral, abdominal and superiliac skinfolds and relative cutaneous temperatures (table 2). The principal anthropometric characteristics of the subject are summarized in table 1.

Table 1. Morphometric data for the subject

	Age	Height (cm)	Mass (kg)	Body mass index (%)	Body fat (%)	Trunk fat (%)	HR basal (bpm)	T_{int} (°C)
Skin diver (man)	28	172	70	23.6	18.4	14.2	58	36.8

Table 2. Plicometer data and relative skin temperature

Landmarks	Skinfold measures (mm)	Skin temperature (°C)
Pectoral	5.0	34.3
Abdominal	12.2	33.3
Superiliac	7.2	33.7

The subject was non-smoker, without cardiovascular or pulmonary disease. He had not taken drugs and he is not under any medications with a potential impact on cardiovascular or thermoregulation functions during the two months prior to the experiment. He abstained from taking alcoholic or caffeine-containing products for a 4-h period prior to the start of the experiment. The subject removed body hair on the trunk so that it was clean and without cosmetics products before the measurements to obtain thermal images most meaningful of skin temperature. Spectral emissivity was set at 0.95 (skin value). Exercise was made on two consecutive days in laboratory with no significant variation of environmental conditions (T, RH, light). Source of artificial or natural heat by radiation was avoided in order to reduce IR radiation noise. The subject was placed in front of a uniform background with a constant temperature ($T = 24.86 \pm 0.20$ °C).

Thermal image sequences of the anterior surface of the subject's trunk were recorded by a 14-bit digital infrared thermo-camera (AVIO, TVS-700, 320 × 240 Microbolometric Array; 8–14 μm spectral range; 0.07 °C thermal resolution; and 35 mm lens). Recordings were made using a digital frame grabber with a rate of two images per second during the trainings and the following recovery time.

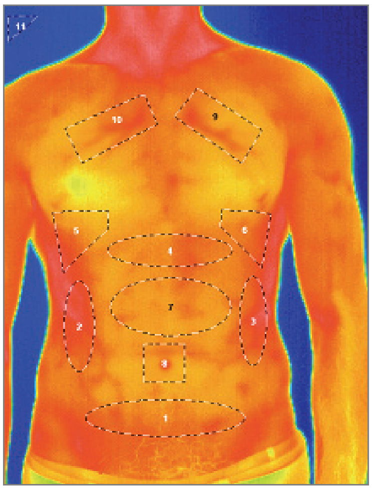

Fig. 1. Infrared image of the subject at rest with the labelled areas put in evidence

Seven Regions Of Interest (ROI) were selected (numbered from 1 to 7) on the trunk following anatomical and functional correspondence with the muscles involved in breathing. Three areas (numbered 8, 9 and 10) were singled out in order to detect body core temperature (figure 1). Area labelled 1 corresponds to the lower part of the rectus abdominus muscle; areas labelled 2 and 3 have been placed symmetrically over the abdominal oblique and transverse muscles; area labelled 4 corresponded to the diaphragm muscle; areas 5 and 6 corresponded to the intercostal muscles; area labelled 7 corresponds to the higher part of the rectus abdominus muscle; area 8 is in correspondence of the navel: areas 9 and 10 were placed on the superior part of the major pectoral muscles and corresponded with external venous circulation local system (branch of external jugular vein), which can be considered as indicator of the blood temperature influenced by those tissues.

The subject acclimated to the room temperature for 10 minutes before the exercise, was set at 115 cm from the thermocamera for all shootings. The subject started a standard respiratory muscle exercise with SpiroTiger® for 5 minutes, followed by 5 minutes of recovery. The exercise was repeated 15 minutes after the end of recovery time. On the first day of trial the subject performed thoracic breathing exercises, while on the second day of trial he performed diaphragmatic breathing exercises using the same protocol.

Table 3. Training parameters and data

	1st day thoracic breathing		2nd day diaphragmatic breathing	
	Exercise 1	Exercise 2	Exercise 1	Exercise 2
Environmental temperature (°C)	24.6	24.8	23.6	24.0
Relative humidity (%)	60	64	59	58
Breathing bag volume (l)	2.8	2.8	2.8	2.8
Breathing rate, acts per minute (apm)	36	36	24	24
Total breathed volume (l)	552	673	474	447

The ROI were defined in the first image of each exercise sequence. 1200 images were recorded for each experiment (600 for exercise and 600 for relative recovery). In order to avoid effects due to subject movement, only a selection of about 100 images for both training and recovery was taken into account. Images were chosen using a selection in the area including shoulder and background pixels: we selected the images with two distinct peaks of Gaussian distribution.

The images of the sequence were then corrected for temperature shift due to the periodic self-calibration of the sensor using area 11 with a constant temperature (in the background) and analyzed with a dedicated software for thermal images elaboration (GRAYESS IRT Analyzer, Version 4.8). The thermal data, for areas from 1 to 7, were extracted calculating the mean temperature of all the pixels in the area. The thermal data for areas 8, 9, and 10, were calculated by considering the warmest pixel in the ROI and taking the temperature value averaged over the 24 pixels around it. This choice is due to the dimension and the irregular thermal distribution of the areas considered that do not correspond to any specific muscular area.

3. Results

Thoracic and diaphragmatic trainings showed two completely opposite behaviors. In thoracic breathing (figure 2) we can see an increase in the heat detected in the upper-thoracic area, and then a progressive decrease in temperature at the end of the training and during the few minutes following it. Instead, in the diaphragmatic breathing, there is a linear decrease starting after the first 50 seconds (figure 3). In this case as well there is a return to the initial temperature after the end of the exercise. Thoracic breathing is characterized by a linear heating during the time of exercise after an initial stationary period of about 100 seconds, and a linear trend in the cooling down process as of the end of the exercise.

An attempt to check functional behavior of respiratory muscles in a specific breathing exercise, was made through the calculation of correlation coefficient among thermal data of all the selected areas. Correlation was calculated separately for both exercise and recovery time.

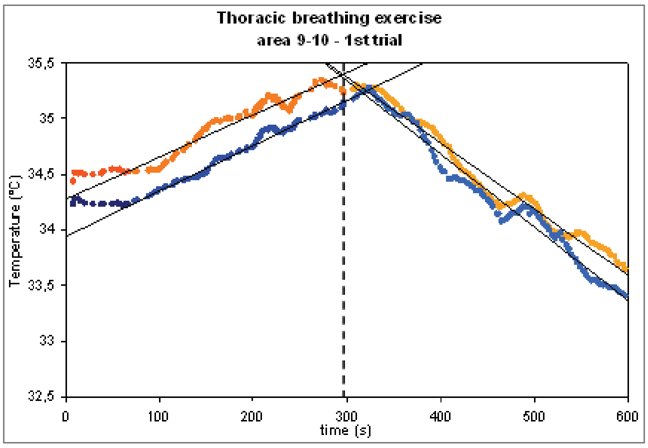

Fig. 2. Temperature values of the region of interest 9 and 10 (inner areas temperature) during the thoracic breathing exercise. The curves show an increment of temperature during the exercise and a decrease from the end of the exercise for the whole recovery. Dotted line corresponds to the end of the exercise

Values of R greater than 0.85 were considered a reliable index of correlation in the behavior of the thermal trend of muscular areas.

Correlation indexes are shown in tables 4 and 5 for thoracic and diaphragmatic respiration, respectively.

Table 4. Correlation indexes in Thoracic Exercise between data of different zones, first trial and second trial

		Thoracic Exercise 1st trial								
		1	2	3	4	5	6	7	9	10
Recovery	1		0.78	0.82	0.88	0.91	0.76	0.92	–0.92	–0.92
	2	0.77		0.95	0.63	0.93	0.84	0.55	–0.81	–0.82
	3	0.48	0.71		0.74	0.97	0.92	0.63	–0.82	–0.79
	4	–0.63	–0.75	–0.18		0.97	0.96	0.95	–0.73	–0.67
	5	–0.44	–0.36	0.21	0.77		0.56	0.67	0.41	0.40
	6	–0.64	–0.73	–0.19	0.98	0.84		0.84	–0.66	–0.59
	7	–0.64	–0.73	–0.17	0.99	0.84	0.99		–0.76	–0.73
	9	–0.70	–0.75	–0.20	0.98	0.84	0.99	0.99		0.98
	10	–0.69	–0.77	–0.20	0.98	0.80	0.99	0.99	0.99	
		Thoracic Exercise 2nd trial								
		1	2	3	4	5	6	7	9	10
Recovery	1		0.98	0.98	0.99	0.97	0.99	0.99	0.40	0.31
	2	0.82		0.98	0.99	0.98	0.98	0.99	0.52	0.43
	3	0.68	0.91		0.97	0.98	1.00	0.98	0.45	0.39
	4	–0.71	–0.50	–0.46		0.98	0.98	1.00	0.52	0.43
	5	–0.01	–0.10	0.13	0.16		0.98	0.98	0.54	0.46
	6	–0.48	–0.14	0.08	0.78	0.38		0.99	0.41	0.34
	7	–0.23	–0.05	0.08	0.69	0.57	0.79		0.49	0.41
	9	–0.90	–0.61	–0.51	0.87	0.01	0.67	0.48		0.97
	10	–0.38	0.04	0.21	0.63	0.25	0.84	0.79	0.68	

Table 5. Correlation indexes in Diaphragmatic Exercise between data of different zones, first trial and second trial

Diaphragmatic Exercise 1st trial										
Recovery		1	2	3	4	5	6	7	9	10
	1		0.37	0.66	0.65	0.29	0.80	0.74	0.78	0.80
	2	0.89		0.84	0.85	0.94	0.55	0.73	0.63	0.76
	3	0.92	0.90		0.99	0.74	0.90	0.96	0.88	0.94
	4	0.94	0.89	0.98		0.76	0.90	0.96	0.88	0.94
	5	0.65	0.59	0.37	0.43		0.45	0.67	0.54	0.68
	6	0.90	0.88	0.98	0.97	0.32		0.93	0.89	0.89
	7	0.95	0.87	0.97	1.00	0.46	0.95		0.96	0.97
	9	0.82	0.71	0.89	0.93	0.30	0.87	0.95		0.95
	10	0.85	0.77	0.92	0.96	0.31	0.91	0.97	0.99	
Diaphragmatic Exercise 2nd trial										
Recovery		1	2	3	4	5	6	7	9	10
	1		0.94	0.97	0.97	0.85	0.95	0.97	0.96	0.96
	2	0.39		0.99	0.97	0.86	0.94	0.97	0.95	0.96
	3	0.44	0.04		0.96	0.84	0.94	0.96	0.94	0.95
	4	0.51	0.17	0.96		0.85	0.95	0.99	0.98	0.99
	5	0.35	0.64	0.12	0.35		0.96	0.90	0.90	0.91
	6	0.47	0.01	0.99	0.98	0.20		0.97	0.97	0.98
	7	0.52	0.17	0.97	1.00	0.33	0.97		0.99	0.99
	9	0.47	0.23	0.94	0.99	0.40	0.95	0.99		1.00
	10	0.51	0.25	0.94	0.99	0.38	0.94	0.98	0.99	

4. Discussion

Following the correlation indexes, it was possible to group thermal data having similar trend. In particular analyzing the first trial of the thoracic breathing exercise, we found a strong correlation for:

- areas 9 and 10, with a correlation index of 0.98. It is interesting to notice that these areas are not correlated with any others;
- the central areas 1, 4 and 7 correspond to the rectus abdominus;
- areas labelled 2 and 3, abdominal oblique and transverse muscles;

In the recovery time, the correlation was different, showing similar trend for:

- areas 9 and 10 (linear correlation index $R = 0.99$);
- areas 4, 6, 7, 9, and 10 (linear correlation index $R \geq 0.98$).

The second trial showed a similar behavior; in the exercise there is an increase of correlation among most of the areas, but in the recovery it is not possible to establish any correlation among muscle areas.

In the first trial of diaphragmatic breathing exercise, as shown in table 5, all the areas are correlated with a high correlation index ($R \geq 0.85$). In the recovery, there is a decrease of the total amount of the correlated areas that results to be:

- areas 3, 4, 6, 7, 9, and 10 ($R \geq 0.96$).

In the second trial, as happens in the thoracic exercise, we found a similar behavior, but in this case with a general reduction of the number of correlated areas for the exercise and an increase of this number during the recovery.

In thoracic breathing the heating-up is linked to the work of the muscles located in the upper part of the trunk [4], [5], which are superficial muscles. The temperature measurements at points 9 and 10 are linked to the vascularity of the part involved in the exercise, and therefore the curve in the graph of figure 2 represents the muscle heat production which is dissipated through circulation. At the very moment in which the exercise ends, the local temperature begins to diminish due to the superficial phenomena of evapo-transpiration, which then leads to a decrease of 0.8 °C compared to the beginning of the exercise.

In diaphragmatic breathing (figure 3), which mainly uses internal musculature [1], [10], temperature does not increase in any areas. What can be understood is that there is obviously a lesser use of superficial muscles engaged in thoracic breathing. In this case, more muscles synergistically participate to carry out an action, and hence each muscle works less [4]. The considerable decrease in temperature compared to the beginning of the exercise is then partially compensated by its increase at the end of the exercise. An explanation for this type of behavior is that the decrease in temperature in the external areas could be due to a flow of blood to the inner part (the diaphragm) [10], hence taking blood away from the external areas. For this reason, heat remains within the body, and what can be observed is a superficial cooling down due to evapo-transpiration which takes place in a very short time (50 seconds). An explanation for the fact that after a resting period, at the end of abdominal respiration, the temperature does not completely return to the values observed at the beginning of the exercise, is that activity in the bulbar respiratory center of the nervous system that has momentarily memorized the modality of breathing (learned but not yet rendered automatic in day-to-day activities) continues to maintain it even after the end of the exercise [5], [10]. The second trials showed a less evident trend of heating and cooling probably due to the influence of the first trial.

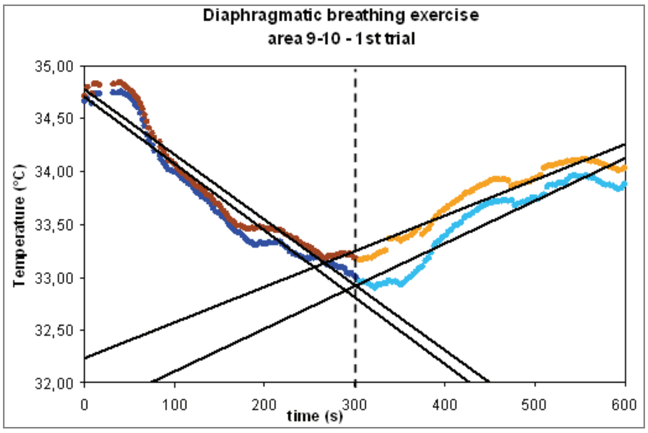

Fig. 3. Temperature values of the region of interest 9 and 10 (body core temperature) during the diaphragmatic breathing exercise. The curves show a decrease during the exercise and an increment when the phase of recovery starts. Dotted line corresponds to the end of the exercise

This study allows us to put in evidence different distributions of skin-temperature between the two types of breathing exercises.

In this preliminary experiment we studied the feasibility of using IR thermography in the respiratory training and quantifying the influence of the breathing on the distribution of cutaneos temperature. In particular we defined the framework of a well defined protocol and the results show significant variations in skin temperature according to different types of breathing. From the examinations of thermal images we stressed different trends of temperature during the exercise and the recovery time. In the thoracic breathing, a temperature rise of 0.90 °C and a decrease of 1.05 °C, while in diaphragmatic breathing a temperature decrease of 1.60 °C and a rise of 1.00 °C are observed. For both types of respiration changes in the slope of temperature trend occur exactly as the exercise ends. We recall that these conclusions valid for one male subject cannot be considered as general.

Future studies will have to tackle the subject matter accounting for important differences concerning mass and fat distribution, in particular, for what concerns female subject.

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