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# Article Infrared Thermography for Real-Time Assessment of the Effectiveness of Scoliosis Braces

Leopoldo Angrisani <sup>1</sup><sup>(1)</sup>, Egidio De Benedetto <sup>1\*</sup><sup>(1)</sup>, Luigi Duraccio <sup>2</sup><sup>(1)</sup>, Fabrizio Lo Regio <sup>1</sup><sup>(1)</sup>, Roberto Ruggiero <sup>3</sup> and Annarita Tedesco <sup>4</sup><sup>(1)</sup>

- <sup>1</sup> Department of Electrical Engineering and Information Technology University of Naples Federico II, Naples, Italy
- <sup>2</sup> Department of Electronics and Telecommunications Polytechnic University of Turin, Turin, Italy
- <sup>3</sup> Ortopedia Ruggiero SRL, Cardito, Naples, Italy
- <sup>4</sup> Department of Chemistry, University of Naples Federico II, Naples, Italy

\* Correspondence: egidio.debenedetto@unina.it (E.D.B.)

Abstract: This work proposes an innovative method, based on the use of low-cost infrared thermog-1 raphy (IRT) instrumentation, to assess in real time the effectiveness of scoliosis braces. 2 Establishing the effectiveness of scoliosis braces means to decide whether the pressure exerted by 3 the brace on the patient's back is adequate for the intended therapeutic purpose. Traditionally, the 4 evaluation of brace effectiveness relies on empirical, qualitative assessments carried out by orthopedists during routine follow-up examinations. Hence, it heavily depends on the expertise of the 6 orthopedists involved. At the state of the art, the only objective methods to confirm the orthopedists' opinion are based on the evaluation of how scoliosis progresses over time, often exposing people to 8 ionizing radiations. To overcome these limitations, the method proposed in this work aims to provide 9 a real-time, objective assessment of the effectiveness of scoliosis braces in a non-harmful way. This is 10 achieved by exploiting the thermoelastic effect and correlating temperature changes on the patients' 11 backs due to the mechanical pressure exerted by the braces. A system based on this method was 12 implemented and validated through an experimental study on 21 patients conducted at an accredited 13 orthopedic center. The experimental results demonstrate a classification accuracy slightly below 14 70% in discriminating adequate from inadequate pressure, which is an encouraging result for further 15 advancement in view of clinical use of such systems in orthopedic centers. 16

Keywords: Health 4.0; Biomedical applications; Instrumentation; Real-time measurements; Real-time17Monitoring; Scoliosis Braces; Infrared Thermal Imaging18

### 1. Introduction

Scoliosis is defined as a complex deformity of the backbone and the torso that occurs 20 in three dimensions [1,2] and consists of a lateral curvature with a vertebral rotation [3]. 21 The standard screening test for scoliosis is the forward bending test [3], during which the 22 patient is asked to bend forward with straight knees, while the examiner observes the 23 back for any signs of asymmetry. If the results of the test, along with the patient's medical 24 history, raise suspicion of scoliosis, radiography becomes crucial for further evaluation 25 [4]. Once radiography is acquired, scoliosis is identified by means of the measurement 26 of the Cobb angle, which quantifies the degree of spinal curvature by measuring the 27 angle between the two most inclined vertebrae at the top and at the bottom of the curve 28 [5,6]. In particular, scoliosis is diagnosed when this angle exceeds  $10^{\circ}$  [7]. Among the 29 different types of scoliosis, idiopathic scoliosis represents the majority of cases since it 30 is identified as a multi-factor spinal deformity with unknown etiology [8]. In addition 31 to the significant cosmetic deformity, idiopathic scoliosis poses risks including cardiac 32 and pulmonary impairments [9]. Based on the patient's age, scoliosis is categorized as 33 infantile (0-3 years), juvenile (4-10 years), and adolescent (older than 10 years) [3]. Other 34 classification systems consider the number of curves and the type of deformity [10]. 35

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With regards to the treatments, they include various approaches such as observation, physiotherapy, bracing, and, in extreme cases, surgery [11]. While surgery is needed for 37 Cobb angles greater than 50° [12], scoliosis braces represent the most widely adopted 38 treatment for patients with incomplete bone growth and Cobb angles ranging between 39 25° and 50° [4,12]. In this particular scenario, patients wear a rigid or semi-rigid corset-40 like device, whose model differs in Milwaukee, Lyonnaise, Cheneau, Sforzesco, Boston, and 41 others [4], based on the patient's bone maturity, Cobb angle, and backbone deformation [4]. 42 The design of this corset is tailored to suit the individual patient's torso, considering the 43 asymmetry caused by scoliosis, while the primary objective is to realign the patient and 44 correct the curvature of the backbone. To achieve this, the corset applies external pressure 45 specifically to the regions of the backbone that are affected by the curvature. 46

During the treatment, regular follow-up examinations are necessary to evaluate brace 47 compliance and adjust the corset according to the changes in the patient's body [13], ensur-48 ing proper pressure application. However, currently, there is no consensus in the literature 49 on the implementation of these brace corrections [12], as well as there is a lack of agreement 50 on the mechanical principles of brace design and manufacturing [8,14]. As a result, the 51 evaluation of the effectiveness of the brace, that means deciding whether the pressure 52 exerted by the brace is considered *adequate* or *inadequate*, relies entirely on the expertise 53 of the orthopedist [2,15]. Hence, the more reliable measure to confirm the orthopedist's 54 opinion is the assessment of curve progression, typically achieved by comparing the Cobb 55 angle measured through radiographic images taken over a specific period of time [16]. 56 As it can be deduced, this approach requires a certain time interval between two measure-57 ments of the Cobb angle. In addition, when using radiographic imaging, the potential risks 58 associated with ionizing radiation exposure constitute a limitation for repeated acquisitions 59 over time. If alternative radiation-free methods, such as Moiré topography [17] or 3D 60 scanning [18], are employed to assess the curve progression and evaluate the effectiveness 61 of the brace, the time horizon between two acquisitions could be considerably shortened. 62 Nevertheless, immediate evaluation remains not feasible, as the gradual reduction of spinal 63 curvature can be achieved only with the prolonged wearing of the brace by the patient. 64 Moreover, another crucial aspect is that failure to wear the corset correctly by the patients 65 could result in a deterioration of scoliosis, even if the corset has been properly designed. 66 Therefore, a comparison between two measurements over time may not accurately reflect 67 the effectiveness of the corset if it is not consistently and correctly worn as prescribed. Consequently, orthopedists still currently lack an objective means of monitoring the effec-69 tiveness of corsets in real-time, which would enable prompt adjustments to be made. A first attempt for enabling real-time evaluation was introduced in [10], where the consid-71 ered technique involved the monitoring of the mechanical pressure exerted by the brace by 72 using pressure sensors positioned between the brace and the patient's backbone. Neverthe-73 less, measuring the pressure between these two surfaces, while consistently moving the 74 sensor, without compromising the accuracy of the measurement, proved to be a challenging 75 task. Therefore, ensuring reliability, repeatability, and cost-effectiveness for widespread 76 implementation in healthcare facilities posed additional complexities. 77

Starting from these considerations, this study presents an innovative, non-invasive, and cost-effective approach to evaluate the effectiveness of scoliosis braces in real-time. The proposed method utilizes low-cost infrared thermography (IRT) instrumentation to acquire the skin temperature of the patients' backs, right after removing the braces.

By processing the acquired temperature data, the developed system is able to determine whether the mechanical pressure applied by the corset was *adequate* or *inadequate* according to the orthopedic prescription and design of the brace. In practical application, this method can provide orthopedists with a reliable and objective assessment, allowing them to promptly identify the need for adjustments to the corset and enhance the scoliosis treatment process. This could represent a possible alternative to reduce the prescription of x-rays. The paper is organized as follows. Section 2 provides a background on IRT technology, with a focus on relevant application scenarios in healthcare. Therefore, Section 3 describes the proposed method in detail. The experimental validation is reported in Section 4, along with the obtained results. Finally, conclusions are drawn and future works are outlined.

#### 2. Background

IRT is a non-invasive technology that relies on the detection and registration of emitted radiation energy at wavelengths ranging from 2 to 15  $\mu$ m [19]. This is achieved through an array of detectors that convert the energy *E* into a thermal image [20], which displays the temperature *T* of the observed objects as per the Stefan-Boltzmann law  $E = \varepsilon \sigma T^4$ , where  $\varepsilon$ represents the emissivity of the objects, which is defined as the ratio between the amount of infrared energy emitted by the object and that emitted by an ideal black body at the same wavelength and temperature [21], and  $\sigma$  is the Stefan-Boltzmann constant.

The amount of energy emitted by an object is influenced by multiple factors, not 101 only including emissivity but also wavelength and surface temperature. As emissivity 102 values vary among different objects, they can emit the same amount of thermal energy even 103 though at different temperatures. Moreover, when utilizing infrared detectors to measure 104 the infrared energy emitted by a specific object, the measured value may not solely reflect 105 the energy emitted by the object itself. As a matter of fact, it is also influenced by the energy 106 absorbed, reflected, and emitted by the surrounding environment [20]. In addition, the 107 measure also depends on the distance of the surface from the camera [22]. 108

IRT technology has experienced widespread adoption across diverse fields, includ-109 ing electrical engineering [23], mechanical engineering [24], agriculture [25], veterinary 110 medicine [26], and healthcare [27]. With specific regards to the healthcare sector, this 111 technology has made significant strides over the years, benefiting from advancements in 112 detector sensitivity, cost reductions [22,28], and suitable integration within the broader 113 context of the 4.0 digital transition, which leverages enabling technologies like Augmented 114 Reality [29], Internet of Things [30], Cloud Computing [31], and Artificial Intelligence 115 [32,33]. As a matter of fact, these advancements are resulting in the development of 116 attached-to-smartphones infrared cameras, which offer improved portability, connectivity, 117 and ease of use without compromising performance compared to traditional devices [34]. 118 This paved the way for the rise of decision-support systems able to furnish healthcare 119 professionals with fast, reliable, and objective results in diverse scenarios, including the 120 evaluation of inflammatory processes [35,36], detection of infections, [37] diagnosis of 121 carpal tunnel syndrome [38], monitoring of diabetes-related conditions [39], and assess-122 ment of eye diseases [40]. In the field of rehabilitation and orthopedics, these systems are 123 used for ergonomic evaluations [41], injury prevention and assessments [42,43], scoliosis 124 diagnosis [44,45], and brace manufacturing [46]. In Figure 1, some of the aforementioned 125 healthcare-related scenarios are illustrated.



**Figure 1.** Examples of adoption of IRT in the framework of (a) evaluation of ocular inflammation [36], (b) ergonomics assessment [41], and (c) diagnosis of carpal tunnel syndrome [38].

All these scenarios require advanced knowledge of the relationship between the human body and the relative emitted thermal energy. Human skin has a constant emissivity in the range 3-15  $\mu$ m of about 0.97  $\pm$  0.05, close to that of the black body [22], while the 129

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contribution to the heat supply emitted by the human body can be mainly related to blood 130 perfusion, metabolism, and external sources [27,47], such as electromagnetic fields, or 131 mechanical loading [27]. In this latter case, the relationship between mechanical loading 132 and emitted thermal energy allows to use of IRT in order to evaluate the stress imposed 133 on a body. The involved analysis is known as Thermoelastic Stress Analysis (TSA) and is 134 based on the thermoelastic effect, which refers to the linear correlation between changes 135 in body temperature (and thus emitted thermal energy) and stress states on the surface of 136 the body, assuming local adiabatic conditions [27]. More in detail, mechanical loading is 137 related to the skin temperature variations on the patients' backs according to (1) [48]: 138

$$\Delta T = \frac{T}{\rho C_{\varepsilon}} \sum \frac{\partial \sigma_{ij}}{\partial T} \varepsilon_{ij} + \frac{Q}{\rho C_{\varepsilon}}$$
(1)

where *T* is the absolute temperature of the body,  $C_{\varepsilon}$  is the specific heat at constant strain,  $\rho$  is the density, *Q* is the heat input, and  $\sigma_{ij}$  and  $\epsilon_{ij}$  are respectively the stress and strain change tensors in the three dimensions, for  $i,j = \{1,2,3\}$ .

Taking all these factors into account, it becomes clear that, in the framework of the evaluation of the effectiveness of scoliosis corsets, TSA could represent a robust fundament that can be exploited to assess, by means of suitable acquisition and processing of the thermal images of patients' backs, whether the pressure applied by the corset is adequate.

#### 3. Proposal

Based on the considerations outlined in Section 1 and Section 2, this study proposes a method that leverages the relationship between skin temperature variations and applied mechanical pressure in order to evaluate if the pressure applied by scoliosis corsets on the patients' backs is *adequate* or *inadequate*, thus facilitating orthopedists' clinical decisionmaking. The proposed method represents *workaround* to the problem of directly measuring the pressure exerted by the brace, which is a task associated with several difficulties, as reported in [10]. Figure 2 schematizes the pipeline of the method. This consists of three major modules, namely *Regions of Interest (ROIs) preparation, ROIs processing*, and *Decision*.



Figure 2. Conceptual description of the proposed method

The *ROIs preparation* module consists of three blocks.
 The first block, named *Images Acquisition*, captures the thermal and corresponding
 RGB images from the dorsum of the patients, right after removing the braces. It
 is noteworthy that the patient's dorsum remains uncovered during this stage. To
 ensure that the bracing effect remains visible, it is recommended to wait no more
 than one minute between the patient removing the scoliosis corset and the start of
 image capture. In fact, the duration of the corset's pressure effect on skin temperature

variation after its removal can be influenced by several factors, such as the duration of brace usage, the intensity of applied pressure, patients' metabolism, sweating, and ambient temperature. This effect may gradually dissipate within a few minutes or persist for an extended period, ranging from several minutes to tens of minutes [49,50]. Hence, a waiting time of less than one minute can be considered as a time to ensure adequate stability in the short term.

In the second block, referred to as the Selection of the ROIs, the orthopedic specialist 168 selects on his/her computer (with the help of cursors) two ROIs from the acquired 169 RGB image: the first ROI corresponds to the area in which the thrust is exerted by the 170 brace, while the second ROI is selected symmetrically to the first ROI with respect to 171 the backbone. It should be pointed out that this selection is guided by the patient's 172 clinical history: the orthopedic specialist has access to the patient's radiography, has 173 knowledge of the diagnosis, knows the type of corset worn, and has the related 174 prescription. As a result, he/she possesses the necessary information to identify the specific region of the back where the corset needs to exert its effect. Nevertheless, to 176 avoid confirmation bias, the selection of the ROIs is not performed directly on the 177 thermal image but rather on the RGB one. 178

Finally, the third block (*Mapping*) is responsible for mapping the selected regions from the RGB image onto the thermal image.

2. Also the *ROIs processing* module is divided into three blocks.

The first block, named Grayscale Conversion, handles the conversion of the thermal 182 ROIs from the RGB color space to grayscale so that the white color is associated 183 with the maximum value of temperature, and the black color with the minimum 184 one. Consequently, each ROI undergoes a transformation from three dimensions (red, 185 green, and blue channels) to one dimension (grayscale) to save computational effort. 186 Then, in the *ROIs Partitioning* block, each ROI converted in grayscale is divided by 187 performing both horizontal and vertical slicing. As a result, each ROI is segmented 188 into  $N \times M$  subregions, where N represents the number of horizontal slices and M 189 represents the number of vertical slices. 190

In this way, the last block, called *Partitions Averaging*, allows performing an average assessment on each of the  $N \times M$  subregions within the partitioned grayscale ROIs. This process generates two vectors, each with dimensions  $[N \times M, 1]$ , corresponding to the averaged values of the temperature for each ROI subregion.

3. These two vectors are compared by means of the *Decision* module.

In particular, a *Statistical Test* is performed between the two vectors in order to evaluate whether there is a statistically significant difference between the means of the two 197 groups represented by the vectors. The output of such a Test is the p-value, which indicates the probability of obtaining test results at least as extreme as the result 199 actually observed, under the assumption that the null hypothesis is correct. In this context, the null hypothesis implies no significant difference between the two vectors, 201 suggesting inadequate scoliosis brace pressure. For this reason, the lower the p-value, 202 the lower the probability of erroneously rejecting the null hypothesis. The utilization 203 of a statistically derived score affords independence from absolute temperature (and 204 consequently, pressure) values measured on the patient's back, which significantly 205 vary among different patients and corsets, given the anatomical distinctions inherent 206 to each individual. As a matter of fact, typical pressure values range from 7 to 10 kPa 207 [51], but these values are subject to significant variability both inter-subject and intra-208 subject. The resulting p-value is compared with a *Threshold* in order to associate it with an *Output* that can indicate whether the scoliosis brace is functioning adequately. 210 More specifically, if the obtained p-value is found to be lower than the threshold value, 211 and if the average temperature of ROI #1 (region where brace pressure is supposed) is 212 greater than that of ROI #2 (region where brace pressure is not supposed), the pressure 213 of the scoliosis corset is indicated as adequate. Conversely, if the p-value exceeds the 214 threshold value, it is indicated as inadequate. The identification of this threshold can 215

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follow an *a priori* model, which is based on prior information, or models based on learning from newly acquired data.



**Figure 3.** Graphical representation of the proposed method: a) Selection of the ROIs; b) Mapping; c) ROIs Partitioning and Grayscale Conversion; d) Partitions Averaging; e) Statistical test; f) Threshold-ing and Output.

A graphical representation of the proposed method is shown in Figure 3. The three modules (*ROIs preparation*, *ROIs processing*, and *Decision*) are highlighted along with the inner blocks related to: the selection of the ROIs (a), the mapping onto the thermal image (b), the partitioning and grayscale conversion (c), the averaging of the partitions (d) which provides two vectors v of length  $L = N \times M$ , the t-test (e), and, finally, the thresholding and output assessment (f), which is 0 if the corset pressure is inadequate, and 1 otherwise. 210 2210 2220 2220 2221 2222 2222 2223

#### 4. Experimental Validation

#### 4.1. Experimental Setup

The acquisition of the thermal images was performed by using the FLIR ONE Pro 231 thermal imaging camera [52], a low-cost attached-to-smartphone camera. The cost of 232 this camera is approximately 450 USD. In terms of metrological performance, the camera 233 provides an accuracy of 3 °C when operated within a temperature range of 15 to 35 °C, and 234 when measuring object temperatures ranging from 0 to 120 °C. The thermal sensitivity is 235 equal to 100 mK. The thermal sensor of the camera operates within a spectral range of 8 to 236 14  $\mu$ m, encompassing the range of interest from 8 to 12  $\mu$ m. The acquired data are stored 237 directly on the smartphone as an image with dimensions of  $1440 \times 1080$  pixels, while the 238 thermal resolution of the camera is  $160 \times 120$  pixels. In accordance with the methodology outlined in [41,42], each patient was positioned at a specified distance from the camera. A 240 marked spot on the floor, situated 1 m away from the IR camera, was designated as the 241 reference point. This approach was employed to ensure the repeatability and reproducibility 242 of measurements, as it allowed to guarantee the same camera's performance in terms of 243 resolution and minimized interference from objects near the patients throughout the entire 244 study. All possible obstacles between the IR camera and the patient's back were carefully 245 avoided. For the sake of completeness, a sketch of the acquisition system is shown in 246 Figure 4. 247



Figure 4. Sketch of the acquisition system.

#### 4.2. Experimental Study

The experimental study was conducted at *Ortopedia Ruggiero*, site in Cardito (Naples, 249 Italy), and included a cohort of 21 patients categorized as juvenile and adolescent, of which fourteen were females. This patients' distribution reflects the evidence that idiopathic 251

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scoliosis is more prevalent in women [53]. All the patients were affected by idiopathic 252 scoliosis and subjected to bracing treatment, hence not under consideration for surgery, 253 with different braces according to the specialist's prescription. For the sake of example, 254 in Figure 5, braces of different models are shown while they are worn by patients. Six 255 patients were affected by dorsal or lumbar scoliosis, and the remaining fifteen suffered 256 from dorso-lumbar scoliosis with a double curve of the backbone. Furthermore, no patient 257 was affected by chronic or acute health conditions that cause temperature changes in the 258 skin surface. Overall, nineteen patients participate in the experimentation once, while two 259 patients were acquired twice during the course of the study. 260



**Figure 5.** Example of different braces models, (a) *Boston*, (b) *Sforzesco*, and (c) *Cheneau*, worn by three subjects involved in the experimental study.

Before the IR acquisition, the patients were asked to avoid stimulant beverages, physical activity, body creams, and wearing jewelry. The experimental study was carried out in a conditioned room, with non-direct airflow at the patients, with a temperature ranging from 19 °C to 23 °C as it is representative of real operating conditions.

Upon patients' arrival at the facility, their radiographs and orthopedist prescriptions were obtained. Subsequently, they were instructed to rest in a designated room for approximately fifteen minutes to acclimate. During this time, the orthopedist conducted a standard examination of the patient, including an assessment of the brace's compliance based on manual procedures.

After acclimatization, patients were instructed to undress and remove the brace, allowing for thermal images of their back to be captured. This step ensured that any obstruction caused by the brace material was eliminated, enabling clear visualization of the thermal effects resulting from the brace's applied pressure. 273 274 275 277 277 277 277

At the end of the experimental study, a total of 21 pairs of RGB/thermal images were obtained (one for each patient). For each RGB image, the medical team selected the ROIs as described in Sec. 3. With regards to the patients who suffered from scoliosis with a single curve of the backbone, only a pair of ROIs was selected. Instead, for those suffering from scoliosis with a double curve, two pairs of ROIs were selected.

#### 4.3. Performance Evaluation

The acquired 36 pairs of ROIs were processed in MATLAB environment as described in the *ROIs processing* module shown in Figure 2. After confirming that the data belonged to a normal distribution (by means of a  $\chi^2$  test), the statistical test chosen to provide the scores associated with each pair of ROIS was the Student's t-test. Therefore, the dataset to

be analyzed was composed of 36 scores  $X_i$ , each one associated with the label  $Y_i$ . In order to evaluate the performance of the developed system in terms of classification accuracy 289 (defined as the percentage of instances X correctly classified) and generalization capability 200 (overfitting prevention), a leave-one-out cross-validation (LOOCV) strategy was applied. 291 LOOCV is a common method used to assess the performance and generalization ability 292 of a classifier in a dataset: it is a form of k-fold cross-validation, where k is equal to the 293 number of instances in the dataset. In LOOCV, the dataset is divided into k subsets or folds, 294 where each fold contains only one instance. The model is trained on k - 1 folds and then 295 tested on the remaining fold. This process is repeated k times, with each instance serving 296 as the test set once. 297

In this study, the training was performed by leveraging a grid search between 1000 different 298 values of the threshold *th*, ranging from 0.005 to 0.500. For each iteration, the threshold 299 value  $th_{max}$  that maximized the classification accuracy on the k - 1 training folds was used 300 on the test fold k. At the end of the LOOCV process, the classification accuracies obtained 301 from each iteration (defined as the percentage of instances correctly classified) were aver-302 aged to obtain a final evaluation of the model's performance. This average performance 303 serves as an estimate of how well the model is likely to perform on unseen data. 304

However, due to the significant class imbalance in the dataset, with only 10 instances 305 labeled as *inadequate/0* pressure and 26 instances labeled as *adequate/1* pressure, a balanc-306 ing procedure was conducted prior to the application of leave-one-out cross-validation (LOOCV). Specifically, ten random subsets were created from the original dataset, ensuring 308 that each subset consisted of 20 balanced instances, with half of them labeled as 0 and the 309 remaining half labeled as 1. The procedure for creating each of the ten random subsets was 310 based on randomly selecting 10 instances of the dataset out of the 26 labeled as 1 (changing 311 the seed each time), to which the 10 instances of the dataset labeled as 0 were added. 312 Therefore, LOOCV was applied for each of the ten subsets, thus obtaining ten different 313 values of averaged classification accuracy and related standard uncertainty (evaluated as 314 type-A uncertainty [54]). In this way, the overall mean value and uncertainty extracted 315 provide a robust indication of the system performance on unseen data. Figure 6 provides 316 an illustration of the conducted evaluation of the system performance. The accuracy A and



Figure 6. Description of the evaluation of the system performance.

the corresponding standard uncertainty u, obtained for each subset and then averaged, are shown in Table 1, expressed as percentages. 319

As visible, the overall mean accuracy  $A_m$  is equal to 65.5%, while the overall standard 320 uncertainty  $u_m$ , evaluated using the first-order law of propagation of uncertainty [54], is 321

Metric	Set #1	Set #2	Set #3	Set #4	Set #5	Set #6	Set #7	Set #8	Set #9	Set #10	Mean
A (%)	70.0	55.0	65.0	75.0	65.0	70.0	60.0	65.0	65.0	65.0	65.5
u <b>(%)</b>	10.5	11.4	10.9	9.9	10.9	10.5	11.2	10.9	10.9	10.9	3.4

**Table 1.** Accuracy (A) and corresponding standard uncertainty (u) obtained for each subset and averaged.

found to be equal to 3.4 %. Assuming a normal distribution and a confidence interval of  $_{322}$  95 %, a coverage factor k = 2 is applied to obtain the expanded uncertainty  $U_m = k \cdot u_m$   $_{323}$  and express the measurement results as  $(65.5 \pm 6.8)$  %.  $_{324}$ 

Taking into consideration the employed instrumentation and the approach used in 325 the experimental study, intentionally designed to simulate real-case scenarios, this result 326 proves to be promising regarding further enhancements and potential clinical applications 327 of the system in orthopedic centers.. By utilizing such a system to assess the effectiveness 328 of scoliosis braces, orthopedic specialists would have an objective support that can significantly contribute to the decision-making process. This could lead to further enhancements 330 in the practice of brace-based treatments, eliminating the need to solely rely on the evalu-331 ation of curve progression over time before making decisions regarding necessary brace 332 adjustments.

#### 5. Conclusion

This work proposed a method based on low-cost infrared thermography instrumen-335 tation for the real-time evaluation of the effectiveness of scoliosis braces. The proposed 336 method leverages the thermoelastic effect to correlate changes in brace pressure with 337 temperature variations on the patient's back. An experimental study at an accreditated 338 orthopedic center was conducted on 21 patients of juvenile and adolescent age, simulat-339 ing real operational conditions and acquiring 36 Region of Interest, each of which was 340 labeled by the medical team. A dedicated algorithm incorporating a typical Machine 341 Learning validation technique was implemented to ensure generalization to unseen data. 342 The experimental results demonstrated a classification accuracy of slightly below 70 %, 343 which represents a promising value considering the use of low-cost instrumentation and 344 intentionally non-ideal experimental conditions.

This study represents a pioneering effort in utilizing systems based on this method for 346 clinical applications. By employing such systems to assess the effectiveness of scoliosis 347 braces, orthopedic specialists can have objective support that significantly contributes 348 to the decision-making process. These findings have the potential to drive further advancements in brace-based treatments, reducing the sole reliance on evaluating curve 350 progression over time before making brace adjustments. Future research will focus on 351 enhancing performance through the implementation of more advanced instrumentation, 352 gathering additional data such as temperature decay curves when patients remove their braces, improving the ROI selection (eventually by means of marker-based approaches), 354 and adopting more sophisticated algorithms to enhance the reliability of this method for 355 orthopedic centers. This also paves the way for new evaluations of the effectiveness of the 356 therapy, based on the observation of the compensation of asymmetric skin temperature 357 distribution along the paravertebral areas over time. 358

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Informed Consent Statement: The study was carried out following the guidelines of the Declaration 367 of Helsinki. Approval from the institutional review committee was not necessary since the data for 368 this study were collected during regular clinical practice. Informed consent from parents or legal 369 guardians of each patient was not required as the data were anonymized in compliance with GDPR 370 regulations, ensuring they no longer pertain to identifiable individuals. Furthermore, the study did 371 not alter or disrupt the physician's clinical practices for the patients in any manner. 372

Conflicts of Interest: The authors declare no conflict of interest.

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