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Case Report

MATLAB Analysis of SP Test Results—An Unusual Parasympathetic Nervous System Activity in Low Back Leg Pain: A Case Report

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Abstract: The Skorupska Protocol (SP) test is a new validated tool used to confirm nociplastic pain related to muscles based on a pathological autonomic nervous system (ANS) activity due to muscle nociceptive noxious stimulation analyzed automatically. Two types of amplified vasomotor response are defined as possible: vasodilatation and vasoconstriction. Until now, amplified vasodilatation among low back leg pain and/or sciatica subjects in response to the SP test was confirmed. This case report presents an unusual vasomotor response to the SP test within the pain zone of a sciatica-like case. Conducted twice, the SP test confirmed amplified vasoconstriction within the daily complaint due to noxiously stimulated muscle-referred pain for the first time. Additionally, a new type of the SP test analysis using MATLAB was presented. The SP test supported by MATLAB seems to be an interesting solution to confirm nociplastic pain related to muscles based on the pathological autonomic reactivity within the lower leg back pain zone. Further studies using the SP test supported by MATLAB are necessary to compare the SP test results with the clinical state and other types of nociplastic pain examination.

Keywords: referred pain; muscle pain; autonomic nervous system; MATLAB; diagnostic; central sensitization

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1. Introduction

Nociplastic pain is a term describing the third category of pain that is different from nociceptive pain, which is caused by ongoing inflammation and damage of tissues, and neuropathic pain, which is caused by nerve damage [1]. The nociplastic pain mechanism is not yet fully understood, but most authors point to the leading role of central sensitization (CS) processes that are involved in nociplastic pain development [2,3]. It is difficult to distinguish nociplastic pain from neuropathic and nociceptive pain, especially because none of the currently used diagnostic methods are unique to one mechanism only [4]. Nociplastic pain is often identified by the absence of features that characterize nociceptive and neuropathic pain. Discrimination between different types of pain remains challenging.

Clinical examination, quantitative sensory testing, and pain-type questionnaires are used for diagnosis [5].

Central sensitization is indicated as the major pathomechanism leading to nociplastic pain conditions [6]. However, there is a lack of objective tools for the confirmation of the central sensitization (CS) process [7]. A possible leading role of the autonomic nervous system (ANS) involvement in the central sensitization (CS) processes has been indicated [2,3,8]. It has been suggested that ANS dysregulation is an important factor in the initiation and maintenance of CS processes [9,10]. Changes in ANS regulation, mainly through the sympathetic branch, provoke nociceptor activation indirectly by a vasoconstriction–vasodilatation imbalance or directly by sympathetic nociceptor activation, resulting in widespread pain, hyperalgesia, and allodynia [11]. Furthermore, the measurement of an autonomic response to stimuli has been suggested as a valuable diagnostic tool [12]. The ANS is an important mediator of a stress response. Thus, applying stress stimuli in chronic pain conditions can provoke overactivity in the ANS, suggesting a pathological state [13]. The stress stimuli recommended for nociplastic pain are pressure, heat, and cold [14]. Our new diagnostic tool—the Skorupska Protocol (SP) test—used to confirm nociplastic pain related to muscles is an example of stress application to provoke a pathological reaction [15]. This test uses nociceptive muscle noxious stimulation under infrared thermal (IRT) camera control to observe distant, atypical vasomotor reactivity due to a pathological ANS response. A series of 320 thermograms segmented automatically allowed us to calculate the size of the pathological autonomic phenomenon and average temperature changes every three seconds of the diagnostic procedure lasting 16 min [16]. The automatic segmentation was performed using MATLAB, which is one of the possible software choices for detailed medical data analysis. We chose MATLAB because it allowed us to show new diagnostic possibilities thanks to its rich built-in libraries and relatively easy solutions for advanced statistics and calculations [17].

The SP test applies thermovision in a newly developed unique way, which is more advanced than previous techniques. Until now, the medical IRT application was based on the side-to-side comparison and thermal asymmetries ranging from 0.3 °C to 0.8 °C in the pain region, which indicated dysfunction of the musculoskeletal system [18]. In contrast, the SP test focuses on the symptomatic side only. The SP test supported by MATLAB allows a more precise observation of the provoked pathological autonomic phenomenon that develops in the patient's daily complaint (coincident with the referred pain zone of the examined muscle) [16]. Thus, the size of the autonomic phenomenon and temperature changes (compared to the state before the stimulation) can be calculated every 3 s of the procedure. Moreover, MATLAB allows a fast analysis of thermal data contrary to the time-consuming manual IRT segmentation. Our previous clinical studies considered the response of active trigger points to the SP test and confirmed amplified vasodilatation within the gluteus minimus referred pain zone among low back leg pain, sciatica, and gluteal syndrome patients [19–21]. Due to the leg pain location variability among patients, the data gathered for the lower leg and analyzed in our previous studies were analyzed anatomically, separately for the thigh, calf, and foot. In addition, the size of the observed autonomic phenomenon and the delta of the average temperature ($\Delta\overline{T}^{\circ}$) were shown as separate trends. This caused difficulties with data interpretation among readers. Thus, further development of the MATLAB analysis to better present the SP test results is necessary.

For the aim of this case presentation, an improved MATLAB-based solution, was adopted to demonstrate unusual vasomotor reactivity due to the SP test, i.e., amplified vasoconstriction coincident with the daily complaint of a man presenting with chronic sciatica-like symptoms.

2. Case Presentation

A 34-year-old man visited the pain clinic with a 6-month history of chronic low back leg pain. The patient was diagnosed with sciatica-like symptoms by a neurologist based on

the bedside examination and MRI results. He reported leg pain as an onset manifestation, which aggravated with time. The patient reported continuous buttock pain going down the posterior thigh and calf and lateral edge of the foot that ranged from five to eight points on the visual analog scale and numbness. The straight leg raise test was negative. The patellar reflex was in norm on both sides, and the symmetrical impairment of the Achilles tendon reflexes was identified. The following results were confirmed through MRI examinations: (right central intervertebral disc herniation, L4-L5-S1 symptomatic disc protrusion, L5-S1 nerve root compression). Functional examinations towards the sacroiliac joint syndrome diagnosis according to the Laslett rule were negative [22]. Low back leg pain due to myofascial pain syndrome was confirmed by a myofascial pain specialist with over 10 years of experience. The diagnosis of trigger points (TrPs) was based on Travell and Simons' clinical criteria [23]. However, the most important of the four essential diagnostic criteria—the taut band—is not accessible for the gluteus minimus muscle, which lies deeper than both gluteus maximus and gluteus medius muscles. Thus, the referred pain pattern provoked by snapping palpation and recognized as a daily complaint is necessary as the confirmatory sign and an additional diagnostic criterion. This corresponds with the newest trigger points diagnostic recommendations [24]. To confirm the diagnosis, first the criterion of TrPs spot tenderness was met, and the two most sensitive spots diagnosed as TrPs were then used as the place of noxious stimulation (the SP test application). Additionally, the referred pain pattern for each of the TrPs in the examined muscles was confirmed according to the newest recommendations [23,24]. Active trigger points that aggravated the patient's complaint were found in the gluteus minimus (posterior part), gluteus medius, and quadratus lumborum muscles.

2.1. Diagnostic Assessment

Finally, to confirm pathological ANS activity, the SP test was applied within two consecutive days according to the protocol established for the gluteus minimus muscle to check the vasomotor response in the zone recognized by the patient as his daily complaint [15,16]. According to our previous study, the validity and reliability of the two diagnostic SP test parameters had almost perfect agreement (e.g., thigh: 0.880 and 0.938; calf: 0.902 and 0.956, respectively) [15]. The case presented in this study was examined based on the SP test protocol published in the validation study [15]. (Figure 1).

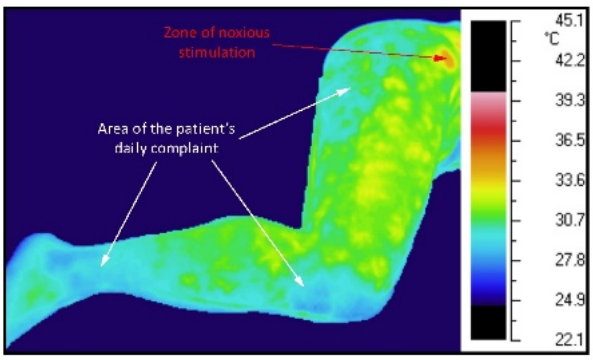

Figure 1. An example of the SP test thermogram with the area of the gluteus minimus noxious stimulation (red arrow) and the lower leg areas associated with the patient's daily complaint and observed towards vasomotor response using an infrared thermal camera (white arrows).

In short, the SP test involved 10-min needle noxious stimulation (fast-in-fast-out dry needling) of the two most sensitive gluteus minimus trigger points that aggravated pain sensations within the referred pain zone. The area of the patient's daily complaint (coincident with the referred pain pattern of the examined muscles) was observed under infrared thermal camera control during noxious stimulation, which was followed by a 6-min post-stimulation observation at rest [20]. Then, all 320 thermograms recorded during the 16-min procedure were segmented automatically by MATLAB to calculate the size and

average temperature changes of the pathological autonomic activity revealed in the area of the daily complaint.

2.2. Procedure in MATLAB

The procedure for the automated analysis of thermographic images recorded during the SP test consists of three steps: (i) the generation of the regions of interest (ROIs) based on manually created masks for the thigh, calf, and foot; (ii) the removal of the outliers and wrong measurement data; and (iii) the calculation of the SP test measures.

Before the automated data analysis was performed in the MATLAB environment, images with the marked ROIs, i.e., the so-called masks, had been prepared manually. The masks were defined anatomically, i.e., for the thigh, calf, and foot. This procedure was performed in the *Paint* editing software. At this time, no procedure has been developed to automatically detect the thigh, calf, and foot in a thermographic image. As a result of the manual procedure, the so-called thigh, calf, and foot masks were developed. A visualization of the masks is shown in Figure 2.

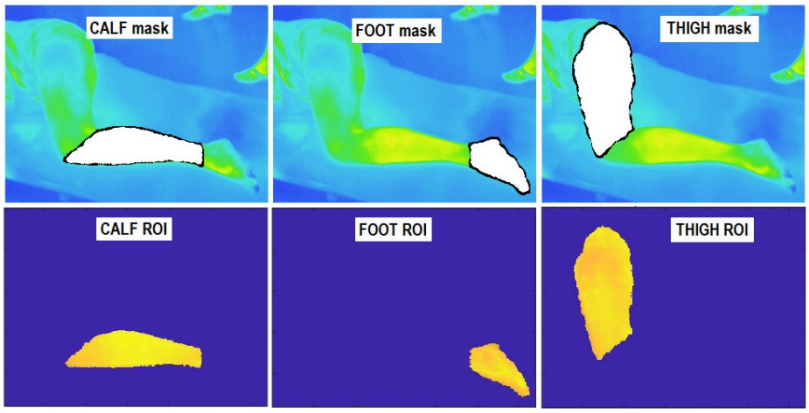

Figure 2. The result of the manual procedure (**upper line**) and the visualization of the matrices for the three ROIs (**lower line**).

Thermograms with masks in the form of a BMP file were loaded into the MATLAB environment to convert them into matrices, which was necessary for further analysis. The procedure of thermogram processing was as follows:

(1) Conversion from a true RGB color image to grayscale using the rgb2gray function. This task was performed by eliminating the hue and saturation information while retaining the luminance. The grayscale values were calculated according to the following formula: $0.299 \times R + 0.587 \times G + 0.114 \times B$, where R is the red component, G is the green component, and B is the blue component. As a result, a 320×240 matrix of values in the range from 0 to 255 uint8 was created;
(2) Conversion of the uint8 values to the float format using the double function;
(3) Reduction of the shadows by eliminating all values but the 255 value, which corresponds to the ROI;
(4) Division of the matrix by 255, which creates a '0'/'1' matrix, where '1' corresponds to the number of pixels within the ROI.

The SP test thermographic images were exported as text files. They were then loaded into the MATLAB environment and stored as a matrix sized 320×240. Each element of the matrix corresponds to a temperature value rounded to one decimal place. The matrices were then multiplied by mask matrices for the three areas: thigh, calf, foot. The mask matrices were calculated according to the procedure described above (points 1–4). The obtained matrices were saved for further calculations.

The SP test evaluates two diagnostic parameters, namely, (i) the autonomic referred pain (AURP), i.e., the percentage area with a temperature response (calculated separately for vasodilatation and vasoconstriction as the size of the region that developed below or

above the baseline maximum and minimum temperature, respectively) and (ii) the level of change in the mean temperature of the area ($\Delta\overline{T}^{\circ}$).

The procedure for the calculation of features and measures:

(1) Calculation of the area with the AURP temperature response in the ROI:

a. Calculate the values of the minimum T_{min} and maximum T_{max} temperature in the first thermogram at the moment T_0 = 0 s:

$$\bigvee T_{px} \in \{1,\ 2,\ \ldots, n\} \wedge\ t = t_0, \quad T_{max} = \max\left(T_{px1}, T_{px2},\ \ldots,\ T_{pxn}\right)$$

$$\bigvee T_{px} \in \{1,\ 2,\ \ldots, n\}\ \wedge\ t = t_0, \quad T_{min} = \min\left(T_{px1}, T_{px2},\ \ldots,\ T_{pxn}\right)$$

b. Calculate the area of the ROI surface A_{ROI} for the patient as the sum of non-zero pixels in the thermogram according to the following equation:

$$\bigvee T_{px} > 0\ ,\ \ A_{ROI} = \sum T_{px}$$

where T_{px} is the temperature value at the pixel px within the ROI;

c. Calculate the percentage of the area with a temperature equal to T_{min} , A_{min} and equal to T_{max}, A_{max} at the moment t_0 according to the following equation:

$$\bigvee T_{px}\ : T_{px} = T_{max}\ \wedge\ t = t_0,\ \ A_{max} = \ \frac{\sum T_{px}}{A_{ROI}} * 100\ \%$$

$$\bigvee T_{px}\ : T_{px} = T_{min}\ \wedge\ t = t_0,\ \ A_{min} = \ \frac{\sum T_{px}}{A_{ROI}} * 100\ \%$$

d. Calculate the percentage of the area with a temperature greater than or equal to T_{max} for $AURP_{T0}$ according to the following equation:

$$\bigvee T_{px}\ : T_{px} \geq T_{max}\ \wedge\ t > t_0,\ \ AURP_{T0}\ =\ \frac{\sum T_{px}}{A_{ROI}} * 100\ \%$$

e. Calculate the percentage of the area with a temperature lower than or equal to T_{min} for $AURP_{T0}$ according to the following equation:

$$\bigvee T_{px}\ : T_{px} \leq T_{min}\ \wedge\ t > t_0,\ \ AURP_{T0}\ =\ \frac{\sum T_{px}}{A_{ROI}} * 100\ \%$$

(2) Calculation of the change in the mean temperature of the ROI:

a. Calculate the value of the arithmetic mean temperature $\overline{T}^{\circ}{}_{tx}$ in subsequent thermograms at the moment t_x, where x = {0, 3, 6, 9, . . . , 900} sec.

b. Calculate the value of temperature changes $\Delta\overline{T}^{\circ}{}_{tx}$ at the t_x moments as the difference between the average temperature values at successive time instants and the value at t_0 according to the following equation: $\Delta\overline{T}^{\circ}{}_{tx} = \Delta\overline{T}^{\circ}{}_{g\_tx} - \Delta\overline{T}^{\circ}{}_{t0}$.

2.3. Results of the SP Test

The SP test confirmed the amplified vasoconstriction coincident with the patient's daily complaint twice. The size of the pathological autonomic reactivity with the $\Delta\overline{T}^{\circ}$ decrease $\geq$0.3 °C that developed due to the noxious stimulation of the muscle-referred pain zone was maximum: first examination (II) = 5.68% and second examination II = 4.89%. The observed phenomenon covered the posterior-lateral thigh and calf. The MATLAB trends show the development of amplified vasoconstriction for the examined patient (Figure 3).

The SP test resulted in: (I) 271 out of 320 measured thermograms (84.7%) from 3′41″ to 16′00″. The greatest $\Delta\overline{T}^{\circ}$ difference was –1.3 °C confirmed at 12′12″ and the lowest $\Delta\overline{T}^{\circ}$ was 0.18 °C at 0′40″. The autonomic referred pain (AURP) phenomenon that developed when the temperature decreased below the minimum temperature recorded before the

stimulation, i.e., thermogram T0, ranged from 0% to 5.68%, with the biggest size value at 9′40″.

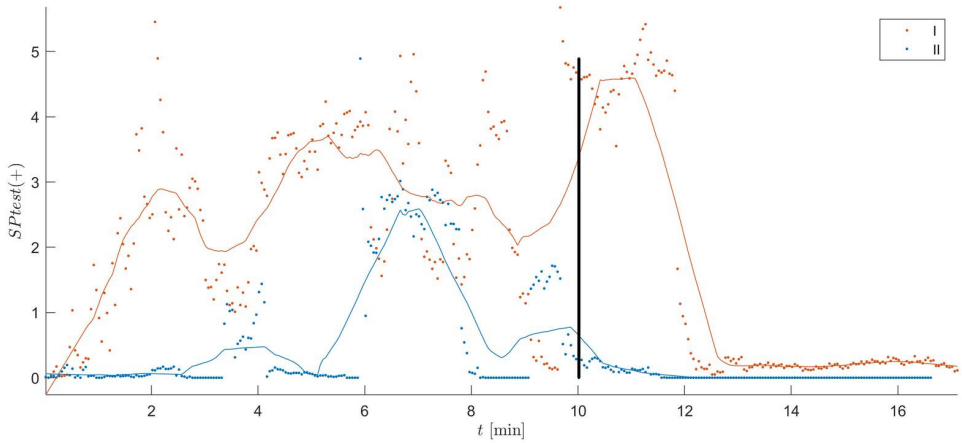

Figure 3. MATLAB trends showing the development of vasoconstriction in the thigh and calf coincident with the area of the patient's daily complaint. Legend: MATLAB trends presenting the development of the percentage size of amplified vasoconstriction in the thigh and calf defined as autonomic referred pain (AURP) and including the condition of a $\Delta\overline{T}^{\circ}$ decrease $\geq$0.3 °C.

(II) A total of 159 out of 320 measured thermograms (49.7%) from 1′50″ to 11′41″. The greatest $\Delta\overline{T}^{\circ}$ difference was −1.5 C confirmed at 13′20″, and the lowest $\Delta\overline{T}^{\circ}$ was 0.2 C at 0′24″. The autonomic referred pain (AURP) phenomenon that developed when the temperature decreased below the minimum temperature recorded before the stimulation, i.e., thermogram T0, ranged from 0% to 4.89%, with the biggest size value at 5′51″.

3. Discussion

This article demonstrated a unique response to the SP test, namely, amplified vasoconstriction observed within the daily complaint of a low back leg pain patient. Moreover, MATLAB trends of the positive SP test results were presented in a novel way (Figures 3 and 4).

Until now, amplified vasodilatation was interpreted as a sign of the pathological autonomic nervous system activity due to nociceptive noxious stimulation, and it suggested a possibility of nociplastic pain among low back leg pain/sciatica patients [19–21].

The validation study was based on the provoked vasodilatation due to the SP test. However, it provided the method description for both autonomic vasomotor responses, i.e., vasodilatation and vasoconstriction, which are characteristic of trigger points, as postulated already by Travell and Simons [25]. The autonomic involvement in the trigger points pathomechanism was indicated as possible by Simons [26]. Furthermore, in the area defined as TrPs, a deregulated motor end plate sustained by a neural loop of sensory and autonomic afferents in the central part of a TrP, and the increased level of biochemically sensitized nociceptors have been confirmed [27]. These bioelectric characteristics can explain the reported skin resistivity decrease in TrPs [28]. All of these data support the findings confirmed by the SP test. Moreover, the newest data in pain medicine explain the autonomic activity within the muscle-referred pain zone to be a result of the peripherally mediated central sensitization process, probably facilitated by sympathetic activity and dysfunctional descending inhibition [29]. Based on that knowledge, our newly proposed diagnostic tool called the SP test, which is intended to confirm an autonomic phenomenon located within the trigger point referred pain zone, seems valuable [16]. At first, the thermographic data were analyzed manually, which was the main disadvantage of the method. The manual data analysis was time-consuming and allowed us to present only an incomplete analysis consisting of three thermograms recorded as (i) the baseline thermogram presenting the initial state before the stimulation, (ii) a thermogram presenting the results at the end of the noxious needling lasting 10 min, and (iii) the last out of 320 recorded thermograms presenting the final result at the end of the 6-min post-needling observation following the

noxious stimulation [15]. Thus, a gap in the data presentation was created, which is finally closed by implementing MATLAB into the procedure [16]. Our previous studies using MATLAB presented the results according to the anatomical scheme published for the lower leg: thigh, calf, and foot. For further SP test development supported by MATLAB, a precise determination of the ROIs was reconsidered. The anatomical ROIs automatically defined by MATLAB were grouped according to the region of the patient's daily complaint (thigh and calf). Thus, the full AURP size with $\Delta\overline{T}^{\circ} \geq 0.3$ °C spreading along the lower leg was presented as one MATLAB trend (Figure 3).

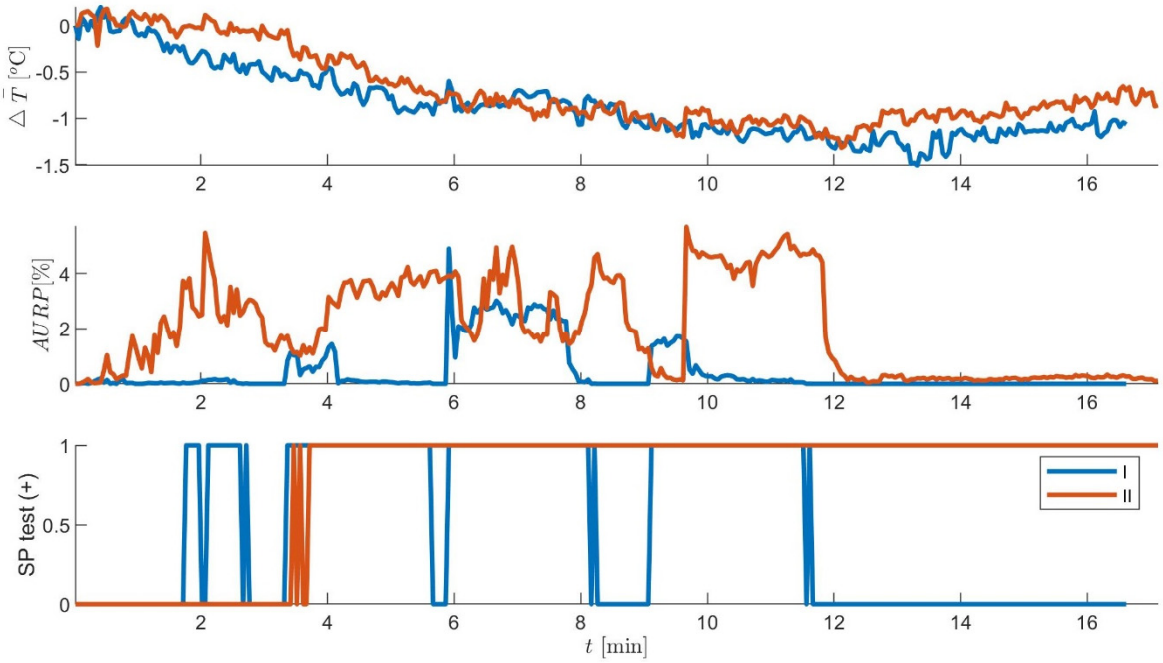

Figure 4. Detailed data of the two SP test diagnostic parameters and the number of positive vs. negative thermograms over time. Legend: (**a**) Development of the $\Delta\overline{T}^{\circ}$ changes over time; (**b**) development of the area with the temperature above the highest recorded in the baseline thermogram (T0) (defined as AURP); (**c**) graph presenting the positive/negative SP test thermograms over time.

This study presented the MATLAB-based analysis of the SP test results as one trend for the whole lower leg for the first time. The analysis revealed the full size of the observed pathological phenomenon with $\Delta\overline{T}^{\circ} \geq 0.3$ °C. This allows a fast SP test results interpretation compare to the previously published studies [16,20]. Muscle-referred pain provoked by trigger points located in the gluteus minimus muscle is a variable that depends on the case. Patients can report muscle-referred pain in the thigh only or spreading down, rarely even to the lateral edge of the foot. Moreover, the data presentation for AURP and $\Delta\overline{T}^{\circ}$ separately hindered the interpretation of a positive SP test. Our last study provided the definition of a positive SP test result, which happens if the AURP occurrence with $\Delta\overline{T}^{\circ} > 0.3$ °C is confirmed. However, the clinical meaning of the number of thermograms that presented positive test results is not clear. As many as most of the thermograms were positive for the case presented in this study. Further studies comparing the SP test results to the clinical states are necessary.

The use of MATLAB software makes thermography more objective and reliable and allows the processing of big data [30]. The automated quantitative analysis used to analyze the thermograms recorded during the SP test renders the procedure results faster and provides lots of additional information concerning the AURP phenomenon and temperature changes that depend on the time of the procedure and the clinical state of the patient. Currently, with the LBP pathomechanism complexity, the diagnosis is very challenging and requires complex clinical decision making to answer the question of what is the

more probable pain generator [31]. A novel idea in pain medicine is to manage low back pain using patients stratification based on clusters of tests and symptoms or—more importantly—on objective parameters [32]. Thus, our newly proposed diagnostic test that shows pathological autonomic reactivity in diseases that have not been considered before as related to the ANS pathological activity seems interesting.

Limitation of the study

Amplified vasoconstriction coincident with muscle-referred pain was confirmed for the first time, but it was based on one case only that was diagnosed with sciatica-like pain. Future studies considering all types of low back pain patients are necessary to assess the incidence of both types of vasomotor responses to the SP test. Moreover, the therapist who performed the dry needling in the present study was not blinded to the trigger-point diagnosis, which could have biased the results to some extent.

Clinical implications

The SP test is intended to objectively confirm muscle-referred pain as a sign of central sensitization related to muscles. Thus, it gives an opportunity to stop controversies around muscle-referred pain presence. The confirmation that both types of vasomotor responses to noxious stimuli are possible indications the sympathetic and parasympathetic involvement in the chronic pain state. It also points to the differences among patients who present with the same disease, which can possibly result in different therapeutic approach requirements. Moreover, it has been confirmed that muscle-referred pain contributes to other diseases such as shoulder pain, neck pain, headache, etc. Further studies considering the use of the SP test for the examination of other muscles that present referred pain are necessary.

4. Conclusions

This case report suggests that both types of vasomotor reactivity are possible within the muscle-referred pain zone. The SP test supported by MATLAB seems to be an interesting solution to confirm nociplastic pain related to muscles based on the pathological autonomic reactivity within the lower leg back pain zone. Further studies using the SP test supported by MATLAB are necessary to compare the SP test results with the clinical state and other types of nociplastic pain examination.

5. Patents

This section is not mandatory but may be added if there are patents resulting from the work reported in this manuscript.

Author Contributions: E.S., T.D., D.W. and M.R. conceived the original study idea. E.S., M.J. and T.D. wrote the first draft of the manuscript. M.J., P.D. (Przemysław Domaszewski), M.K. and P.P. provided input for the analysis and interpretation of data. E.S., M.R. and T.D. performed the investigation. P.D. (Paweł Dobrakowski) supervised. All authors have read and agreed to the published version of the manuscript.

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

Abbreviations

IRT	infrared thermography
ANS	autonomic nervous system
TrPs	trigger points
AURP	autonomic referred pain
ROI	Region of Interest
$\Delta\overline{T}^{\circ}$	delta of the average temperature
CS	central sensitization
Tmin	minimum temperature
Tmax	maximum temperature
T0	temperature of the baseline thermogram (T0)

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