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Systematic Reviews and Meta-analysis
about Infrared Thermography in Musculoskeletal Research:
trends and critical appraisal

Plantar Foot Assessment
Using Liquid Crystal Thermography

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Contents

Systematic Reviews and Meta-analysis about Infrared Thermography in Musculoskeletal Research: trends and critical appraisal

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SUMMARY

BACKGROUND: The number of systematic reviews and meta-analyses reporting the value of infrared thermography has been increasing and are mostly published in health-related subject areas, such as musculoskeletal research. Although this type of research has received much attention, the information regarding the characteristics and overall methodological quality is not known.

OBJECTIVE: T To evaluate the publication trends and methodological quality of systematic reviews and meta-analyses reporting the value of infrared thermography in musculoskeletal research.

METHODS: A systematic review was conducted up to August 2022 and systematic reviews aiming to report the value of infrared thermography in musculoskeletal research were included. Data regarding study information, aim of the review, number of studies included, and main conclusions were extracted, and the type of systematic review was determined. The Joanna Briggs Institute Critical Appraisal Tool for Systematic Reviews and Research Syntheses was used to assess the methodological quality of the included studies.

RESULTS: Fifteen systematic reviews were included, mostly classified as diagnostic (66.7%). All studies had methodological quality issues and the confidence in the results of systematic reviews was classified as low in 33.3% and critically low in 66.7% of the studies.

CONCLUSION: The quality of systematic reviews is very low and there is a need to improve the quality of systematic reviews and meta-analyses reporting the value of infrared thermography in musculoskeletal research

KEYWORDS: Infrared Thermography; Systematic Reviews; Methodological Quality

SYSTEMATISCHE ÜBERSICHTSARBEITEN UND METAANALYSEN ZUR INFRAROT-THERMOGRAPHIE IN DER MUSKULOSKELETTALEN FORSCHUNG: TRENDS UND KRITISCHE BEWERTUNG

HINTERGRUND: Die Zahl der systematischen Übersichtsarbeiten und Metaanalysen, die über den Wert der Infrarot-Thermografie berichten, hat zugenommen und wird meist in gesundheitsbezogenen Themenbereichen wie der muskuloskelettalen Forschung veröffentlicht. Obwohl dieser Art von Forschung viel Aufmerksamkeit geschenkt wurde, sind die Informationen über ihre Merkmale und die allgemeine methodische Qualität nicht bekannt.

ZIEL: Bewertung der Publikationstrends und der methodischen Qualität systematischer Übersichtsarbeiten und Metaanalysen, die über den Wert der Infrarot-Thermographie in der muskuloskelettalen Forschung berichten.

METHODEN: Ein systematischer Review wurde bis einschließlich August 2022 durchgeführt und systematische Review-Artikel mit dem Ziel, den Wert der Infrarot-Thermografie in der muskuloskelettalen Forschung zu berichten, wurden eingeschlossen. Daten zu Studieninformationen, Ziel der Überprüfung, Anzahl der eingeschlossenen Studien und wichtigsten Schlussfolgerungen wurden extrahiert und die Art des systematischen Reviews wurde bestimmt. Das Joanna Briggs Institute Critical Appraisal Tool for Systematic Reviews and Research Syntheses wurde verwendet, um die methodische Qualität der eingeschlossenen Studien zu bewerten.

ERGEBNISSE: Es wurden fünfzehn systematische Übersichtsarbeiten eingeschlossen, die meist als diagnostisch eingestuft wurden (66,7%). Alle Studien hatten methodische Qualitätsprobleme und das Vertrauen in die Ergebnisse systematischer Übersichtsarbeiten wurde in 33,3% der Studien als niedrig und in 66,7% der Studien als kritisch niedrig eingestuft.

SCHLUSSFOLGERUNG: Die Qualität systematischer Übersichtsarbeiten, die den Wert der Infrarot-Thermographie in der muskuloskelettalen Forschung berichten, ist sehr niedrig und es besteht die Notwendigkeit, die Qualität systematischer Übersichtsarbeiten und Metaanalysen zu verbessern.

SCHLÜSSELWÖRTER: Infrarot-Thermografie; Systematische Übersichtsarbeiten; Methodische Qualität

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Introduction

Thermal imaging has been used to study a number of diseases where skin temperature can be useful to assess the presence of inflammation in underlying tissues, or where blood flow is altered due to a clinical abnormality and can be applied in either as a diagnostic test or as an outcome measure for clinical trials [1].

Systematic reviews and meta-analyses are robust, reproducible, and structured secondary research studies that combine the results of primary research studies, providing a more accurate description of the analysed phenomenon. This type of research has an important role in evidence-based practice, since well conducted systematic reviews produce high quality evidence on diagnostic accuracy or effects of interventions [2, 3]. According to Munn et al. [4] there are 10 typologies of systematic reviews but this idea of robust, reproducible, structured critical synthesis of existing research is common in all of them.

Over the years, the number of systematic reviews and meta-analyses reporting the value of infrared thermography has increased (Figure 1), mostly published in health-related subject areas (Figure 2), and musculoskeletal health is one of the most popular research fields.

In 2020 and 2021 the increase in the number of published systematic reviews was much more pronounced with 36 published in 2020 and 51 published in 2021. This increase is interesting and probably related to the COVID-19 pandemic since primary research was heavily affected and researchers had to maintain their scientific production.

However, little is known about the characteristics of these systematic reviews, concerning the topic, type, and overall methodological quality. Therefore, this study aims to evaluate the publication trends and methodological quality of systematic reviews and meta-analyses reporting the value of infrared thermography in musculoskeletal research.

Methods

The review was reported based on the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [5].

Eligibility Criteria

Only systematic reviews with or without meta-analysis aiming to report the value of infrared thermography in musculoskeletal research were included.

Search Strategy

A systematic electronic search was conducted up to August 2022 in Pubmed, Web of Science and Scopus using the search string ("thermal imaging" OR "infrared imaging" OR thermog*) AND ("systematic review" OR "meta-analysis") in the title, abstract and keywords and filtering for review articles. Secondary searches were conducted on the reference lists and citation tracking of included studies to identify other possible relevant systematic reviews, and the same search string was used in Google Scholar and the first 200 results were screened but no additional result was included.

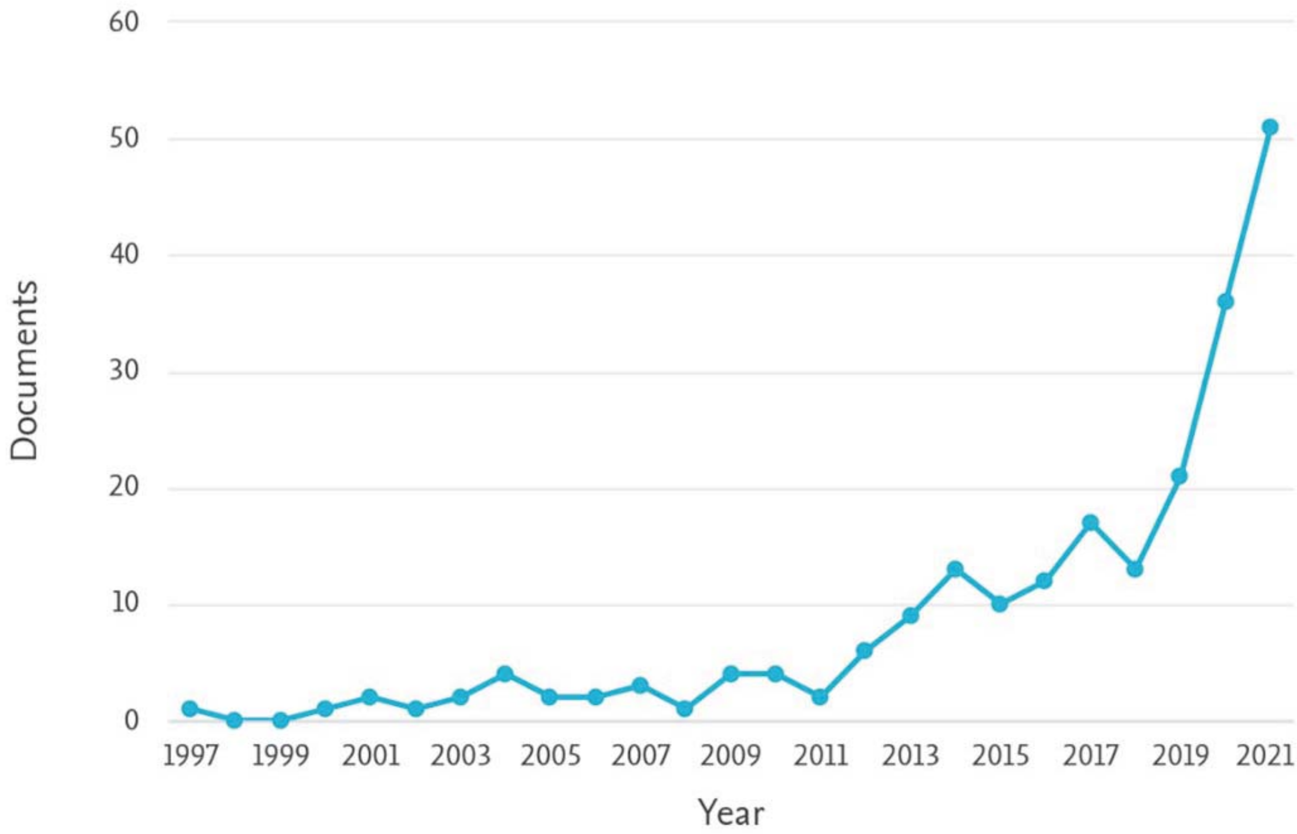

Figure 1
Systematic reviews related to infrared thermography by year of publication. Source: Scopus search: TITLE-ABS-KEY (("thermal imaging" OR "infrared imaging" OR thermog*) AND ("systematic review" OR "meta-analysis")) AND (LIMIT-TO (DOCTYPE, "re")).

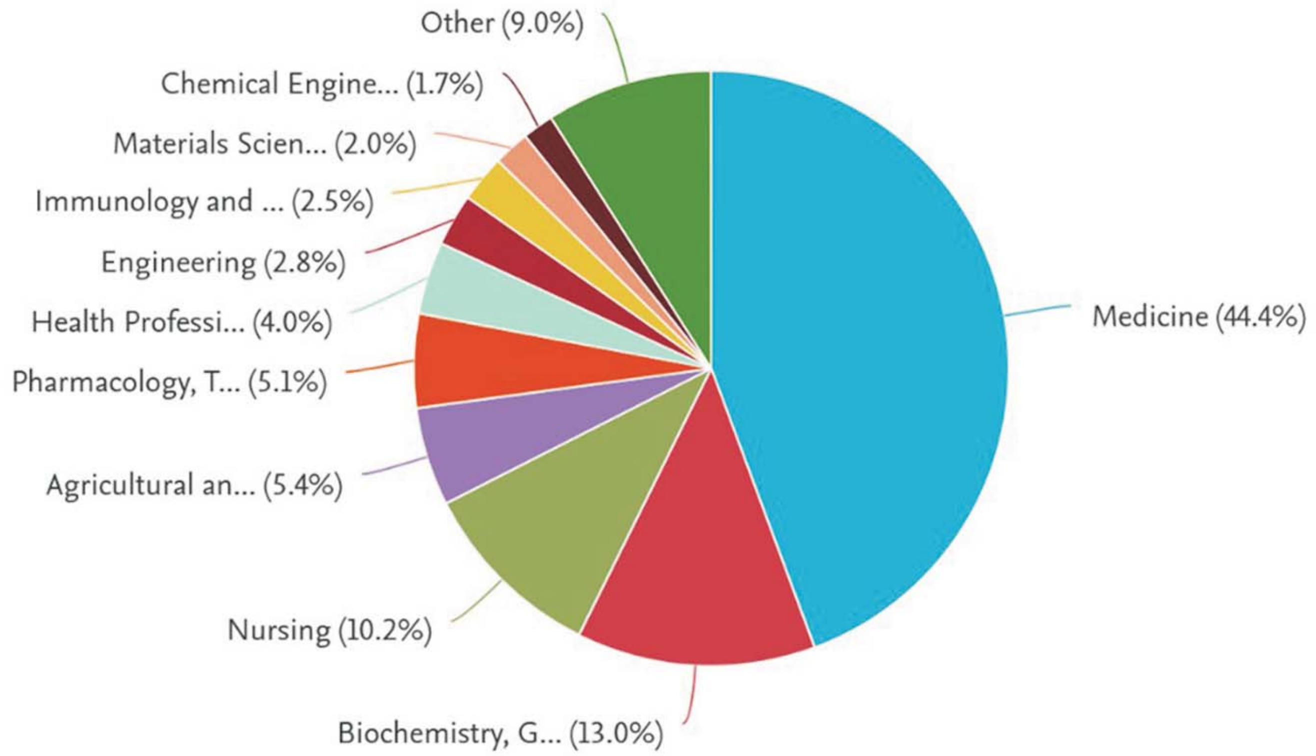

Figure 2:
Areas of publication of systematic reviews related to infrared thermography by year of publication. Source: Scopus search: TITLE-ABS-KEY (("thermal imaging" OR "infrared imaging" OR thermog*) AND ("systematic review" OR "meta-analysis")) AND (LIMIT-TO (DOCTYPE, "re")).

Study Selection and Data Extraction

All references were exported to data management software (EndNote X9), and duplicates were removed. The review was conducted following three steps. Records were identified through a database search and reference screening (Identification) and two reviewers (AS, KA) independently examined the titles and abstracts and irrelevant studies were excluded based on eligibility criteria. Relevant full texts were analysed for eligibility (Screening), and all relevant studies were included in the systematic review (Inclusion). Any disagreement was resolved through discussion, until consensus was achieved.

The same researchers were responsible for data extraction from the included studies. Data regarding study information (author and year), aim of the review, number of studies included (sample size), and main conclusions were extracted.

Critical Appraisal of Included Studies

The type of systematic review was determined according to the Munn et al. criteria [4] and the Joanna Briggs Institute (JBI) Critical Appraisal Tool for Systematic Reviews and Research Syntheses [6] was used to critically appraise the quality of the included systematic reviews by two reviewers (AS, KA). Any disagreement was resolved through discussion, until consensus was achieved. Comprehensive literature search, assessment of risk of bias for individual studies, appropriate data synthesis methods, consideration of risk of bias in result interpretation, and assessment of presence and impact of publication bias are domains often considered as critical in the methodological quality of systematic reviews. The JBI tool items 3 (Was the search strategy appropriate?), 4 (Were the sources and resources used to search for studies adequate?), 5 (Were the criteria for appraising studies appropriate?), 6 (Was critical appraisal conducted by two or more reviewers independently?), 8 (Were the methods used to combine studies appropriate?) and 9 (Was the likelihood of publication bias assessed?) assess those critical domains. Considering these domains, the overall confidence in the results of systematic reviews was classified as "High" (none/one non-critical issue), "Moderate" (>1 non-critical issue), "Low" (one critical issue) and "Critically Low" (>1 critical issue).

Results

A total of 460 studies were identified through a database search and, after the removal of duplicates, 336 distinct studies were identified. During the screening process, 319 publications were excluded for not being related to the research question, and the full text of 17 studies was reviewed in detail. After careful analysis, 2 studies were excluded (1 [7] because the review was not focused on infrared thermography and 1 [8] because it was not a systematic review).

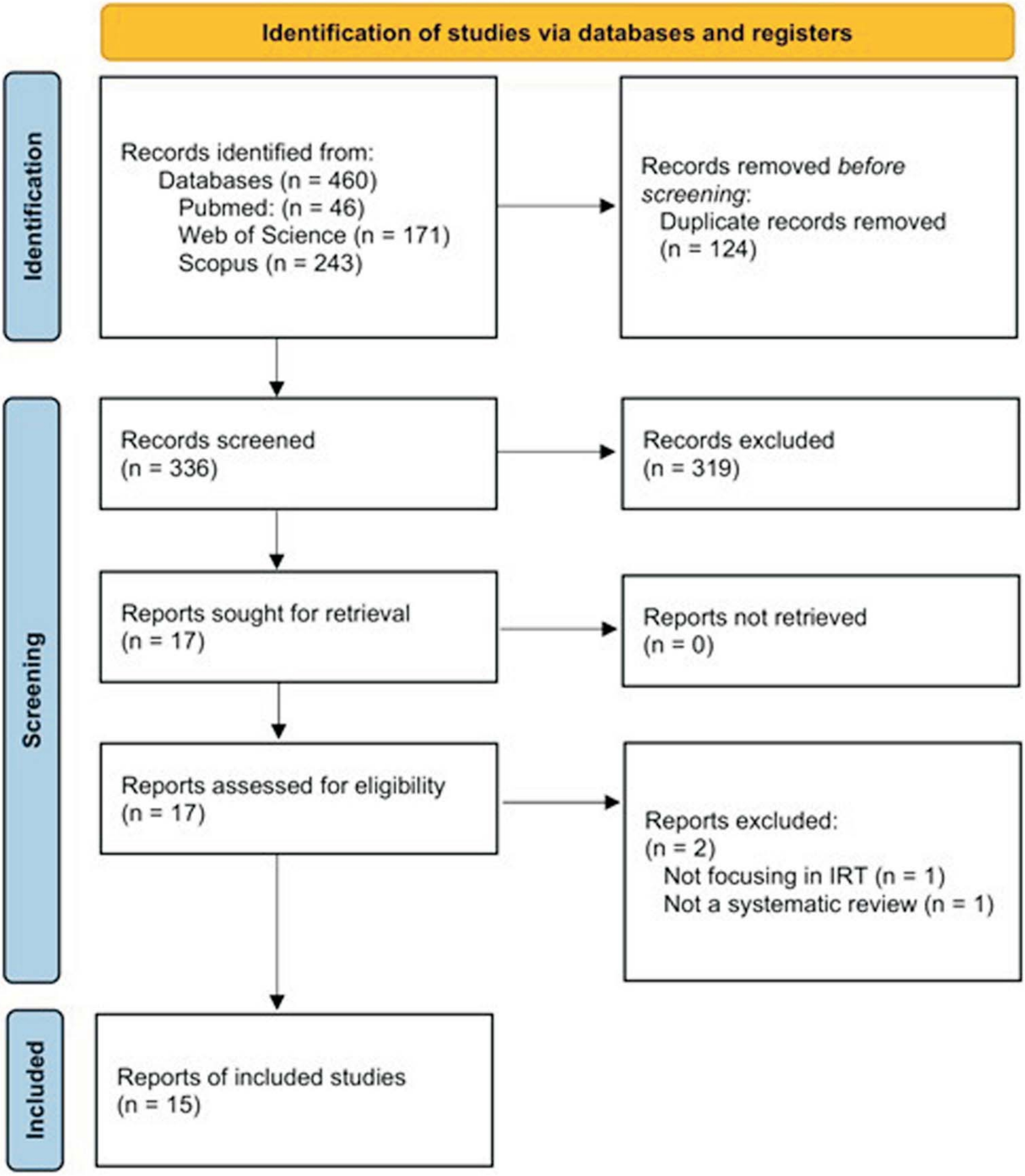

Figure 3:
PRISMA flow diagram of the literature selection process.

Finally, 15 studies were included in the systematic review. The selection process is schematized in Figure 3.

According to the Munn et al. criteria [4], 10 (66.7%) systematic reviews were classified as diagnostic, 5 (33.7%) were classified as prognostic, 3 (20%) were classified as effectiveness and 3 (20%) were classified as prognostic systematic reviews (Figure 4).

Most reviews focused on musculoskeletal conditions in general (4, 26,7%), 3 (20%) focused on temporomandibular joint conditions, 2 (13.3%) focused on spine conditions, 2 (13.3%) focused on rheumatic conditions, 1 (6.7%) on tendinopathies, 1 (6.7%) on arm and forearm issues, 1 (6.7%) on periprosthetic joint conditions, 1 (6.7%) on muscle injuries and 1 (6.7%) on bone fractures.

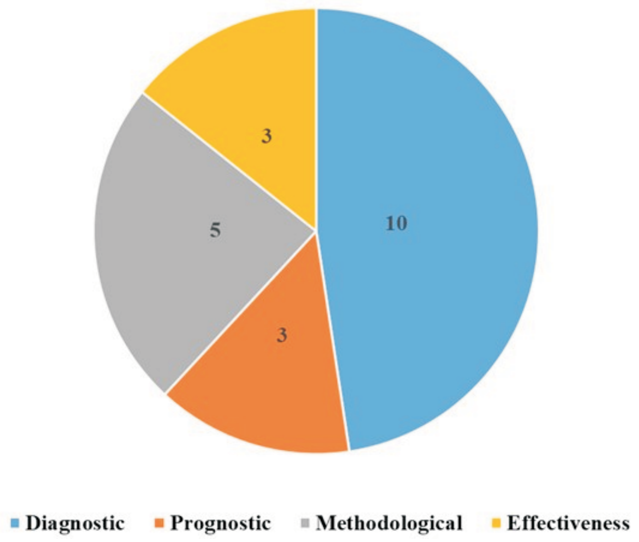

Figure 4:
Type of systematic review according to Munn et al. criteria [4]

The information regarding author, year, aim of the review, number of studies included, and main conclusions of the included systematic review can be found in table 1.

The results for critical appraisal are represented in Figure 5. All studies had methodological quality issues and 12 (80%) of the 15 included reviews failed to provide appropriate specific directives for future research. Critical appraisal of included studies was also an issue, with 6 (40%) failing to provide adequate critical appraisal and 10 (66.7%) failing to critically appraise the included studies by two reviewers. Most studies (9, 60%) have not used appropriate methods to combine studies, especially those using qualitative synthesis, and 8 (53.3%) failed to provide an adequate search strategy and to provide recommendations for policy and/or practice supported by the reported data. The resources used to search for studies, the criteria for appraising the included studies and the clarity of the review question were an issue in 6 (40%) of included reviews. From the 4 systematic reviews using quantitative synthesis, all used appropriate methods to combine studies but only 1 (25%) assessed the likelihood of publication bias correctly.

Table 1:
Summary table of the selected studies regarding author, year, aim of the review, number of studies included and main conclusions.

Study	Aim of the review	Number of studies	Main conclusions
Hoffman et al. [9]	To evaluate Infrared Thermography diagnostic accuracy and clinical utility for lumbar radiculopathy.	28	Considering the critical flaws of the published literature, the role of Infrared Thermography remains unclear
Sanchis-Sánchez et al. [10]	To determine the diagnostic accuracy of Infrared Thermography in the diagnosis of musculoskeletal injuries	6	The published literature does not support the usefulness of infrared thermal imaging in musculoskeletal injuries diagnosis
Chaudhry et al. [11]	To critically evaluate the application of Infrared Thermography for detecting and staging tendinopathy	6	Infrared Thermography is a potentially valuable tool in the detection of abnormal thermal patterns associated with tendinopathy.
de Melo et al. [12]	To analyse the value of Infrared Thermography in the diagnosis of temporomandibular joint disorders.	9	The available literature is not sufficient to assess the value of Infrared Thermography in the diagnosis of temporomandibular joint disorders.
Fathima & Dharman [13]	To analyse the existing clinical trials of the role of thermography in diagnosis of orofacial pain.	6	Infrared Thermography can be helpful in evaluating myogenous temporomandibular disorder and can be used as a clinical screening method and for improving diagnostic accuracy
Vardasca et al. [14]	To identify the outcomes and proposed further research lines of biomedical musculoskeletal applications of IRT in the arm and forearm, mainly in physical evaluation, to aid new experiments, major developments and contribute to a wider acceptance and use of this imaging technique.	33	Infrared Thermography has the potential to provide physiological information on the arm and forearm, showing potential to serve as an aid in various pathologies and health situations.
Bunn et al. [15]	To evaluate the effectiveness of infrared thermal imaging in detecting musculoskeletal injuries non-elderly people.	6	Infrared Thermography had a good diagnostic value for musculoskeletal injuries.

Table 1continued

Study	Aim of the review	Number of studies	Main conclusions
Scheidt et al. [16]	To determine whether reference literature exists for the infrared thermographic examination of knee and hip arthroplasty and if reference values can be derived for the methodology or if there is a peri- and postoperative benefit.	5	Infrared Thermography is a useful procedure in the perioperative monitoring of patients following endoprosthetic joint replacement of the knee and hip
Viegas et al. [17]	To review the use of IRT for the functional evaluation,identification and prevention of muscle injuries, and comment on the control variables used in its applicability	12	Infrared Thermography is a suitable tool for evaluation and prevention of muscle injuries in athletes, and care should be taken with the control variables during its use.
Albuquerque & Lopes [18]	To evaluate the role of infrared thermography as a helpful outcome measure tool in subjects with back and neck syndromes	16	More than a diagnostic tool, thermography can be an objective tool for monitoring the effectiveness of treatment by identifying deviations from a healthy state. Thermography also seems to have an association with patients' complaints, particularly with the presence and intensity of musculoskeletal pain..
Moreira et al. [19]	To assess the role for thermography in clinical assessment of musculoskeletal and temporomandibular disorders	25	Healthy individuals are expected to have equivalent temperature values in contralateral or homologous regions. For unilateral symptomatic individuals, the affected orofacial region is expected to vary more than 0.4°C in comparison with the healthy contralateral site. The accuracy of Infrared Thermography for diagnosing musculoskeletal disorders and temporomandibular joint disorders is still low to moderate. Infrared Thermography is a valid and reliable complementary approach for the diagnosis and follow-up of musculoskeletal disorders and temporomandibular joint disorders.
Schiavon et al. [20]	To assess the potential and limitations of thermography in the study of the inflammatory component of joint inflammatory and degenerative diseases.	32	Infrared Thermography can be used in addition to the currently available tools for screening, diagnosis, monitoring of disease progression, and response to medical treatment.
Branco et al. [21]	To summarize and describe the clinical applicability of Infrared Thermography in rheumatic diseases	12	Infrared Thermography is applied in the assessment of rheumatic diseases that involve changes in the distribution of body temperature, as in Raynaud's Phenomenon, as well as in the verification of the effectiveness of medications on the symptoms of rheumatic diseases.
Lubkowska & Pluta [22]	To discuss the medical applications of IRT for musculoskeletal system diseases, with particular emphasis on its usefulness in assessing the therapeutic effects of physical procedures used in rehabilitation	34	Thermovision is an undeniably important diagnostic tool in the physiotherapeutic methods used in musculoskeletal dysfunctions.
Strasse et al. [23]	Investigate studies using medical thermography for the diagnosis fractures and clinical follow-up of bone healing	12	The diagnosis of bone fractures by Infrared Thermography has high sensitivity, reliability, and efficacy as a complementary method for monitoring and it can minimize the use of ionizing radiation-based examinations such as X-rays.

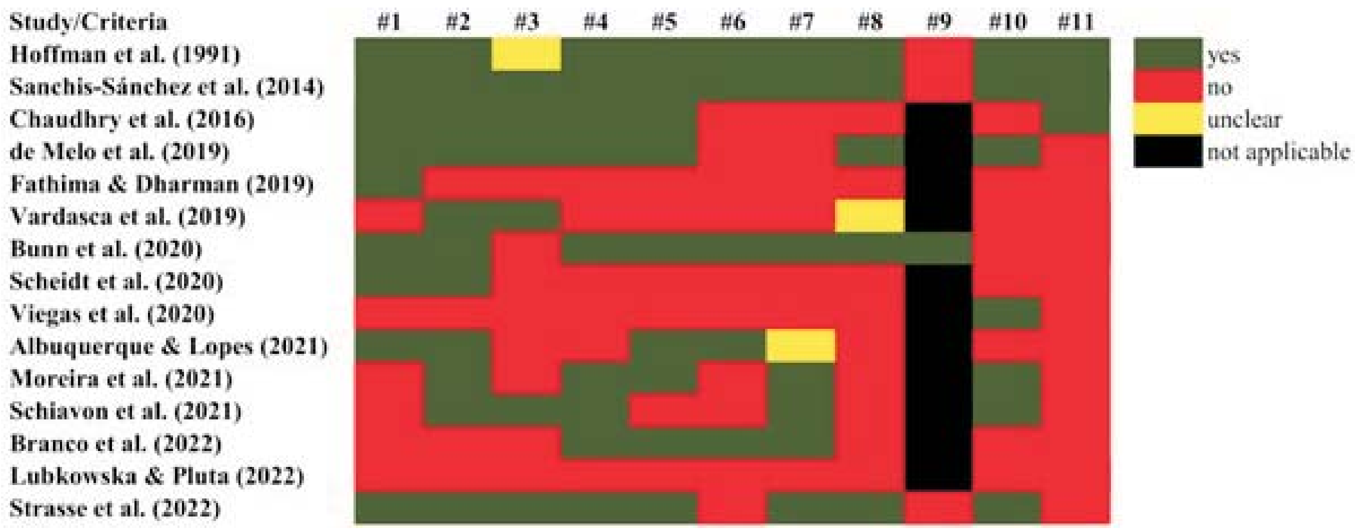

Figure 5:
Critical appraisal of the included systematic reviews (Joanna Briggs Institute Critical Appraisal Tool for Systematic Reviews and Research Syntheses). Note: (1) Is the review question clearly and explicitly stated?; (2) Were the inclusion criteria appropriate for the review question?; (3) Was the search strategy appropriate?; (4) Were the sources and resources used to search for studies adequate?; (5) Were the criteria for appraising studies appropriate?; (6) Was critical appraisal conducted by two or more reviewers independently?; (7) Were there methods to minimize errors in data extraction?; (8) Were the methods used to combine studies appropriate?; (9) Was the likelihood of publication bias assessed?; (10) Were recommendations for policy and/or practice supported by the reported data?; (11) Were the specific directives for new research appropriate?.

Considering the critical domains (items 3, 4, 5, 6, 8 and 9), the overall confidence in the results of systematic reviews was classified as low in 5 (33.3%) and critically low in 10 (66.7%) systematic reviews (Figure 6).

Most systematic reviews were published in the last 3 years and no defined trend in evolution of quality of publication is identifiable.

Discussion

The aim of this study was to evaluate the publication trends and methodological quality of systematic reviews and meta-analyses reporting the value of infrared thermography in musculoskeletal research. To the best of our knowledge, our study is the first investigating the general characteristics and assessing the methodological quality of systematic re-

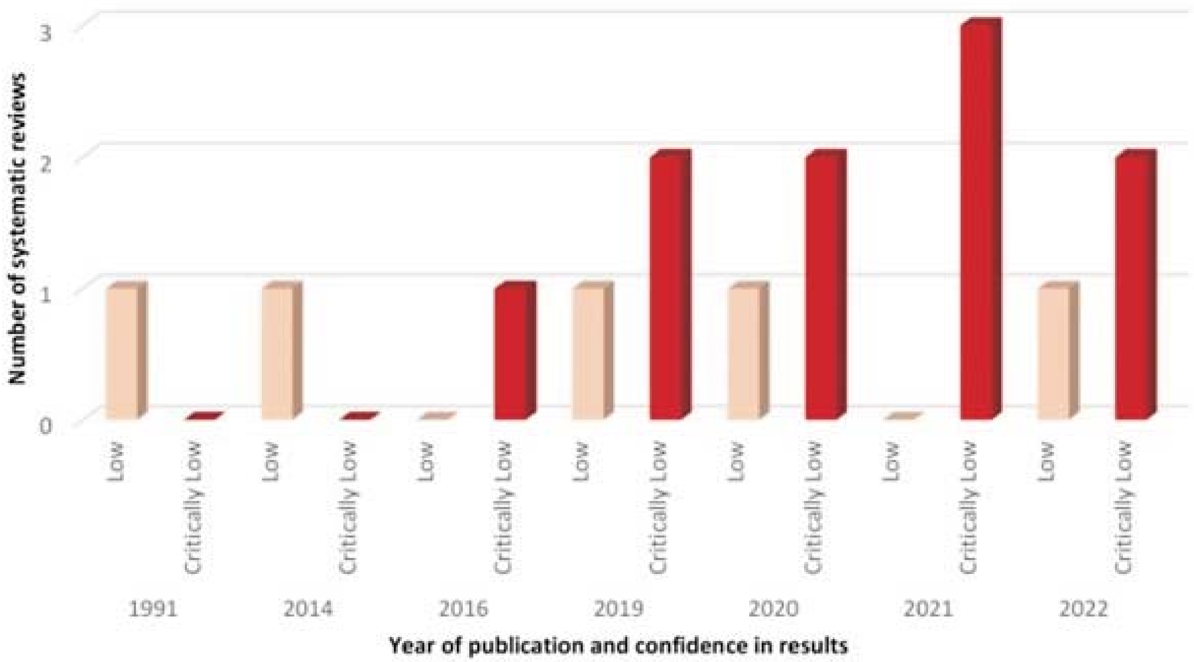

Figure 6:
Time trend of publication confidence in the results of systematic review

views reporting the value of infrared thermography in musculoskeletal research.

The main findings were that most published systematic reviews were related to diagnosis, followed by those related to methodological issues and then by prognosis and effectiveness; that most systematic reviews were published in the last three years; and that the overall quality of the systematic reviews is low and the overall confidence in the results of the majority of systematic reviews is "Critically low". Moreover, although the popularity of this type of publication is increasing over the years there is no trend of improvement in methodological quality, which is a matter of concern.

There are currently available tools and guidelines that, if used by authors, journal editors and peer-reviewers, may improve the quality of reporting and peer-review, such as PRISMA [5] and tools to assess the methodological quality of systematic reviews (e.g. JBI tool and AMSTAR II). Almost all included systematic reviews state that they follow PRISMA guidelines, however, it is frequent to detect directives that were not followed or clearly reported.

Few systematic reviews had clearly defined research questions framed by the Patient, Intervention, Comparison and Outcome (PICO) strategy and a previously established protocol. A prior developed review protocol before performing the review can reduce the risk of bias and promotes research transparency [24, 25]. Platforms such as the International Prospective Register of Systematic Reviews (PROSPERO) are available for such registration. Any deviation from the established protocol should be justified in the review. As stated before, few systematic reviews had previously established protocols and one of those that registered a protocol had important deviations from what was previously established without any justification [21].

Failing to provide relevant information, impairing the reproducibility of the search strategy, which is one of the main pillars of the systematic review process, must be avoided. An extensive and transparent search process is the best way to avoid publication bias [3]. Most systematic reviews have not used adequate search strategies and resources to search for studies. Often the reported search strategy could not be reproduced and, although searching scientific databases and reference lists of included studies, very few systematic reviews have demonstrated any efforts to identify relevant grey literature. It is desirable to search relevant grey literature sources such as reports, dissertations, theses and conference abstracts and Google Scholar may be a good source of information and authors should focus on the first 200 to 300 results of the search [26].

Another critical issue was the assessment of the risk of bias of included studies. In many reviews the risk of bias was not assessed, and in most of those where it was, it was not assessed by two independent reviewers and its potential impact on the results, which is essential to evaluate the validity of the systematic review results [3], was not considered.

When performing meta-analysis, objective methods to combine individual studies are implemented but, when performing qualitative synthesis, combining studies in systematic reviews can be challenging. This issue is more problematic when research questions are not specific, and authors include different types of primary studies (e.g. diagnostic and intervention studies). This was the case in many of the included systematic reviews, making it difficult to understand and interpret the results of the evidence synthesis.

We would like to acknowledge that the present systematic review has some limitations. Only 3 databases were included and searching in different literature sources could have provided additional studies. However, Google Scholar was also searched and no additional result was added, which increases the confidence of the depth of the literature search. To assess the methodological quality of the included systematic review, the JBI Critical Appraisal Tool for Systematic Reviews and Research Syntheses was used. Although we are aware of the AMSTAR II tool, which is highly used, the JBI tool is easier to apply and provides information regarding the relevant domains to critically assess systematic reviews. Moreover, the JBI tools are also widely known and used in scientific literature.

Conclusion

Consistent methodological quality issues were identified in the included systematic reviews, particularly in providing appropriate specific directives for future research, in using adequate critical appraisal methods and appropriate methods to combine studies, in the use of adequate search strategies and resources to search for studies and in providing recommendations for policy and/or practice supported by the reported data.

The existing systematic review quality is very low and not convincing regarding the utility of infrared thermography to diagnose and monitor musculoskeletal disorders. Attention is needed when analysing research about this topic. There is a need to improve the quality of future systematic reviews and meta-analyses reporting the value of infrared thermography in musculoskeletal research and the methodological quality of future primary research on the topic, especially regarding the issues raised in the present review.

Journal editors, which are gatekeepers of the quality of the research that is published, should require the submission of a methodological checklist, such as PRISMA, and encourage peer-reviewers to use quality assessment tools, such as A MeaSurement Tool to Assess systematic Reviews (AMSTAR) II and JBI tool, to improve the quality of the peer-review process of systematic reviews.

Acknowledgements

This paper is an extended and updated version of the conference paper "Systematic reviews and meta-analysis about infrared thermography in musculoskeletal research - trends and critical appraisal", published in Thermology International [27].

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Plantar Foot Assessment Using Liquid Crystal Thermography

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SUMMARY

Thermography can be a powerful tool to monitor foot health. In particular in the area of diabetes research suggests that frequent thermographic assessment may be able to prevent potentially deadly complications such as those arising from diabetic foot ulcers.

This paper introduces a device based on liquid crystal technology that is used by clinicians within the workflow of a foot examination protocol. A second, proposed, version of the device is intended to satisfy the need for frequent assessment at home. In contrast to thermal camera based approaches it should be usable daily by patients at home without many of the constraints of the strict examination protocols that are usually required for such examinations.

Relaxing the protocol constraints means that assessments based on absolute temperatures cannot be used because some parameters under which the thermograms are taken are variable, unknown or not repeatable. The authors therefore suggest a set of measures based on relative temperatures and thermal patterns that are assumed to be more resilient to such variable conditions.

Using 4 case studies as examples the paper examines the advantages and disadvantages of the proposed measures.

KEYWORDS: liquid crystal thermography, diabetic foot, protocol, home assessment, histogram

BEURTEILUNG DER FUßSOHLEN MITTELS FLÜSSIGKRISTALLTHERMOGRAFIE

Die Thermografie kann ein leistungsfähiges Werkzeug zur Überwachung der Fußgesundheit sein. Insbesondere im Bereich der Diabetesforschung deuten Forschungsergebnisse darauf hin, dass eine häufige thermografische Beurteilung potenziell tödliche Komplikationen, wie sie beispielsweise durch diabetische Fußgeschwüre entstehen, verhindern kann.

In diesem Artikel wird ein Gerät vorgestellt, das auf der Flüssigkristalltechnologie basiert und von Klinikern im Rahmen der Erstellung eines Fußuntersuchungsprotokolls verwendet wird. Eine zweite, vorgeschlagene Version des Geräts soll häufige Fußuntersuchungen zu Hause ermöglichen. Im Gegensatz zu wärmebildkamerabasierten Ansätzen sollte es täglich von Patienten zu Hause verwendet werden können, ohne viele der Einschränkungen durch strenge Untersuchungsprotokolle, die normalerweise für solche Untersuchungen erforderlich sind.

Die Lockerung des Untersuchungsprotokolls bedeutet, dass Auswertungen auf der Grundlage absoluter Temperaturen nicht verwendet werden können, da einige Parameter, unter denen die Thermogramme aufgenommen werden, variabel, unbekannt oder nicht wiederholbar sind. Die Autoren schlagen daher eine Reihe von Maßnahmen vor, die auf relativen Temperaturen und thermischen Mustern basieren, von denen angenommen wird, dass sie gegenüber solchen variablen Bedingungen widerstandsfähig sind.

Diese Arbeit untersucht anhand von 4 Fallstudien die Vor- und Nachteile der vorgeschlagenen Maßnahmen.

SCHLÜSSELWÖRTER: Flüssigkristallthermografie, diabetischer Fuß, Protokoll, Beurteilung zu Hause, Histogramm

Thermology international 2022, 32(4) 74-81

Introduction

In a typical podiatric clinic in the United Kingdom 13% of patients in the age group between 55 and 64 are living with diabetes. This figure rises to almost 17% in the group between 65 and 74 and to 24% in those older than 75 years old [1]. The figures for other countries are similar [2].

Podiatric and vascular specialists are aware that this significant patient cohort is at risk of developing a range of foot complications which, when left untreated, can result in foot ulcers (in the UK 70,000 to 90,000 patients have ulcers at any moment in time) and amputations (9,150 in 2019). 40% of diabetic foot ulcer patients die within 5 years and 50% of amputees survive only 2 years [3].

Underlying research by Armstrong et al. [4] and Bus et al. [5] demonstrated that thermography is suited to detect diabetic foot complications at an early stage where ulceration and subsequent amputations may be prevented, provided the thermographic examination is undertaken at regular intervals, ideally daily.

This is problematic because unless the subject is a hospital inpatient such a regular regime is obviously only possible if patients can undertake the examination themselves at home as part of their daily routine. This raises a range of challenges:

1.Thermographic cameras are too complex to be used reliably in a home environment.

2.Using an infrared camera to self examine feet is physically difficult, in particular for the patient cohort in question who are frequently elderly, overweight or visually impaired.

3. It is practically impossible to enforce a highly repeatable best practice [6] thermographic image acquisition regime.

4. The thermographic data must be easily and quickly transferrable to clinical specialists who knows their patients and their medical history.

Over the last 5 years the authors developed a device for professional use in podiatry that is based on liquid crystal technology. This professional device, its methods, functionality and some case studies are presented in this paper together with a proposal for a new liquid crystal device for home use and methods that address the above problems.

Methods

Thermochromic Liquid Crystal Technology

Thermochromic liquid crystals (TLCs) are chemical compounds that are at the same time ordered (crystallised) solids and unordered isotropic liquids. This dual property is addressed in the name 'liquid crystal'. TLCs have the ability to change colour when exposed to different temperatures and have been in use in medical thermography for over 40 years [7]. The most common form of deployment is to enclose small amounts of liquid crystal material in transparent spheres called microcapsules that are only a few micrometres in diameter. The spheres protect the material from environmental influences and chemical degradation, giving them a usable lifespan of several years. The encapsulation also allows the material to be mixed into an aqueous liquid to form a slurry that can be sprayed onto a carrier material where the liquid evaporates, leaving a thin film of liquid crystal containing microcapsules.

Different chemical compositions can be created to adjust the colour change behaviour, i.e. at what point the TLCs start changing their colour and the range over which the changes occur. Typically, TLCs are entirely transparent above and below their chromatically active range. Therefore, when applied on top of a black background, a sheet covered with TLC "ink" appears black below the start temperature. Then, as the temperature gradually increases, the sheet appears first red, then yellow, green, blue and purple before becoming transparent again at the upper end of the active range and thus ending in the black colour of the background.

The reader may notice that this colour change flow is in the exact opposite direction of that in the frequently used rainbow colour scale in thermal cameras. TLC colours can therefore be somewhat counter-intuitive to interpret. When taking electronic images from such a sheet it is, however, relatively straightforward to invert the colour flow using standard computerised image processing techniques so that the user is presented with an image that conforms to expectations.

The Devices

The authors developed the Podium Professional device shown in Figure 1. It has the size of a bathroom weighing scale but unlike such a scale it is deliberately shaped as a tall wedge to prevent users from standing on it, which in the envisaged patient demographic could create a significant risk of falls and injuries. Instead the patient uses the device while being seated on a chair, couch or bed.

The top of the device is covered by a strong clear poly- carbonate carrier plate on which thermochromic liquid crystal sheets can be placed.

The device for professional use features 3 exchangeable sheets that are laminated to exchangeable rigid polycarbonate plates. These 3 sheets have overlapping and narrow temperature ranges (18°C to 27°C, 21°C to 32°C and 26°C to 36°C) which results in a high thermal resolution of approximately 0.2°C in each sheet. Having exchangeable sheets allows the clinician to select the most appropriate one for a specific patient. It also facilitates the fast repetition of a thermal scan by swapping out plates.

Figure 1:
The current Podium Professional with fixed thermal sheets on the left and the Podium Home (under development) on the right

In the proposed device for home use a single flexible sheet with a temperature range from 18°C to 36°C will be employed. This is a compromise between the advantage of simpler use and the disadvantage of lower temperature resolution because the wider temperature range means that the colour change of the liquid crystals is also stretched out wider than in the professional sheets. Consequently the perceivable thermal resolution (even by computer vision) is only about 0.5°C. This is, however, thought to be good enough for detecting the majority of the pathological changes the device was designed for. The rationale for this is provided in points 1. and 2. in section 'The Detection Approach' below

In both devices the active thermochromic side of the sheets is pointing away from the foot and downwards into the device where a wide angle electronic visual light camera is taking snapshots of the thermal imprints produced by the liquid crystals. The camera is connected to an embedded microprocessor that converts the colours to temperatures. The processor is in turn connected via Bluetooth™ to a small tablet computer where images can be studied and from where they can be forwarded to a central server for remote access by clinicians using a standard web browser interface.

The sheets in both devices can also be removed from the top carrier plate to take visual light images of the plantar feet. This serves to remotely assess if blanching of foot areas under pressure contact with the plate is occurring (absence of blanching is, for example, frequently observed in neuropathic feet) and to inspect the feet for foreign bodies, build-up of callus or skin cracks.

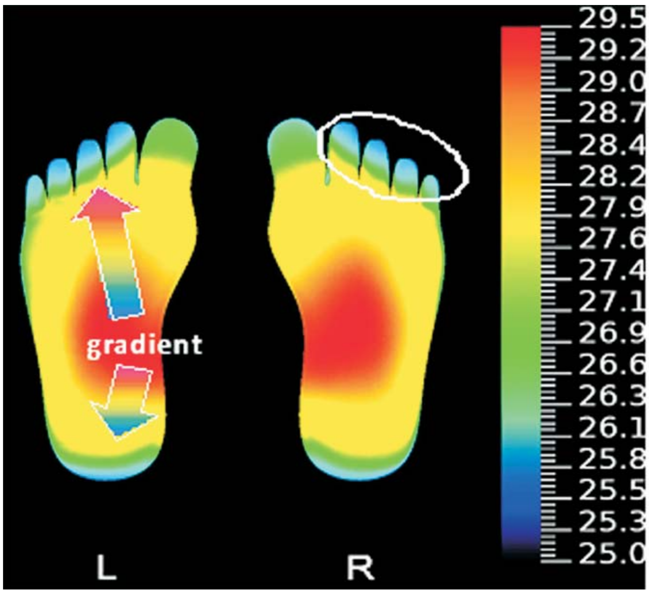


Figure 2:
Thermal pattern of a normal healthy foot artificially created by averaging the thermograms from 100 healthy volunteers. Note the strong contralateral symmetry (e.g. big toe left vs. big toe right, heel left vs. heel right, etc), the descending temperature gradient from medial arch to toes and heels, the very similar temperatures in the little toes and the absence of hot spots and extended cold areas

The Detection Approach

As already mentioned above it is not possible to enforce a repeatable and standard-compliant thermal imaging regime in a home environment. This also applies to a considerable extent to a busy podiatric clinic where time is of the essence. Any image interpretation method must therefore be as independent as possible from variations to the thermal image capture process. Absolute temperatures in particular cannot be used as they are extremely susceptible to changes in subject preparation, timings and environmental conditions.s.

Instead the authors propose to use a set of indicators that are derived from the knowledge of how a healthy foot appears in a thermal image. Any significant deviation from this normal appearance could then be an indicator for a pathological phenomenon.

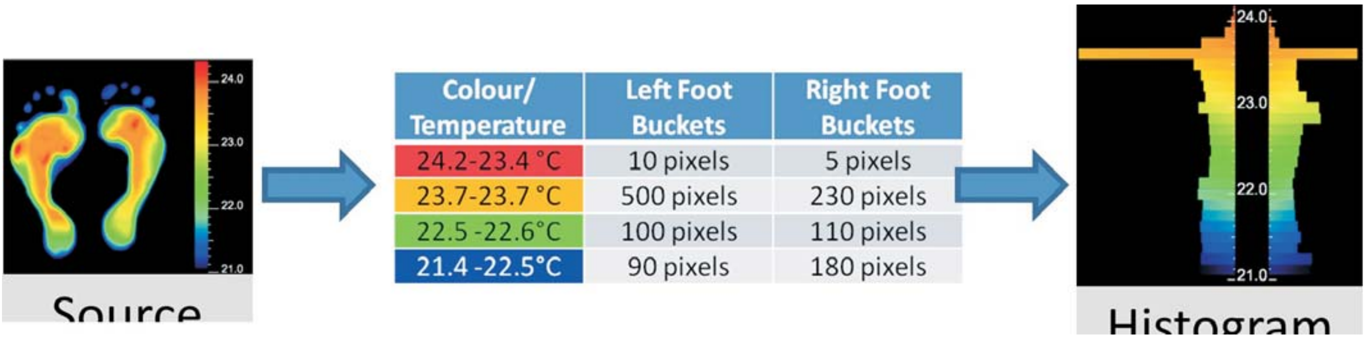
To arrive at a representation of "thermal normality" one of the authors (Kluwe [8]) amalgamated thermal images from the soles of 100 healthy volunteers to create a thermal pattern that represents an average healthy foot. This pattern is shown in figure 2. In this pattern 4 properties are noticeable:

1. **Contralateral symmetry.** This means that corresponding aspects of the left and the right foot (e.g. left big toe vs. right big toe, left heel vs. right heel) are at the same temperature. Work by Macdonald et al. [9] confirmed what is shown in figure 2: healthy feet are highly symmetrical in their absolute and relative temperature distributions. In 99% of all healthy people the contralateral temperature difference between corresponding parts of the left and the right foot differ by less than 1.8°C [9]. The group around van Netten [10] arrived at a slightly higher temperature of 2.2°C, possibly due to the use of a different measurement protocol. Conversely, a difference of more than 1.8°C to 2.2°C is a strong indicator of a potential pathological process.

This 1.8°C difference is obviously not a hard cut-off line but instead a gradual risk indicator. The higher the asymmetry, the higher the likelihood of a pathological condition being present. In this context the thermal resolution of 0.2°C in the professional device is adequate. In the proposed home device is also sufficient because its purpose is to provide early warning signals only that can then either be confirmed or rejected by subsequent clinical investigations.

Because this temperature difference is relative between the left and right foot the assumption is that a change of parameters such as patient preparation or environmental temperature will have only a small impact because both feet are always affected in the same way. However, this assumption, while likely to be true and observed in many instances, is yet to be proven universally valid and more research is needed for confirmation.

2. There exists a strong **thermal gradient** of approximately 7°C between the medial arch and the toes and heels respectively. This phenomenon was labelled the "symmetric bilateral butterfly pattern" by Nagase et al.[11] and



Colour/ Temperature	Left Foot Buckets	Right Foot Buckets
24.2-23.4 °C	10 pixels	5 pixels
23.7-23.7 °C	500 pixels	230 pixels
22.5 -22.6°C	100 pixels	110 pixels
21.4 -22.5°C	90 pixels	180 pixels

Figure 3
A typical thermal image created by the Podium device and its associated combined left-right histogram. The table in the middle shows the pixel count for 4 selected temperature ranges.

found to be present in 48% of all healthy people. The second most common pattern found in 23% of the population is the "whole high" where the gradient is much reduced or almost absent. Therefore complete absence of this gradient or even a reversal may be indicative of an underlying problem.

As under point 1. above this is also a gradual indicator of risk and the limited thermal resolution of the 2 devices is not problematic in the context of the devices' function as a diagnostic adjunct.

3.The **little toes tend to have the same temperature** with the big toe being slightly warmer.

4.Other than shown in figure 2 there should be **no isolated hot spots or cold areas.**

Analysis Aid - The Histogram

A temperature histogram is a visual statistical tool where several "temperature buckets" are shown as vertical or, as here, horizontal bars. Each of these buckets represents a temperature range, e.g. 20.0 °C to 20.2 °C, and is shown in the colour that represents that range in the thermal image. The buckets are filled by counting every pixel in the thermal image into its respective bucket. Therefore, the more pixels are in a particular temperature range, the larger the bucket colour bar for this range becomes. The Podium software produces a combined dual histogram for each scan - one for the left and one for the right foot. They are shown side by side in figure 3.

It is important to note that the histogram is location agnostic: it is possible to create a perfectly symmetrical histogram even if the contralateral symmetry between feet is broken. As such the histogram's value in determining contralateral symmetry is currently limited. The authors are therefore working on an algorithm that creates a left-right differential map of the plantar foot area. This is not a trivial task because it requires the algorithm to recognise the corresponding regions in each foot even if, for example, parts of a foot have been amputated. The current histogram will, however, show differences when the overall temperature of one foot is different from the other.

Results

Typical results obtained with the device and analysis tools outlined above are demonstrated in the 4 case studies shown below:

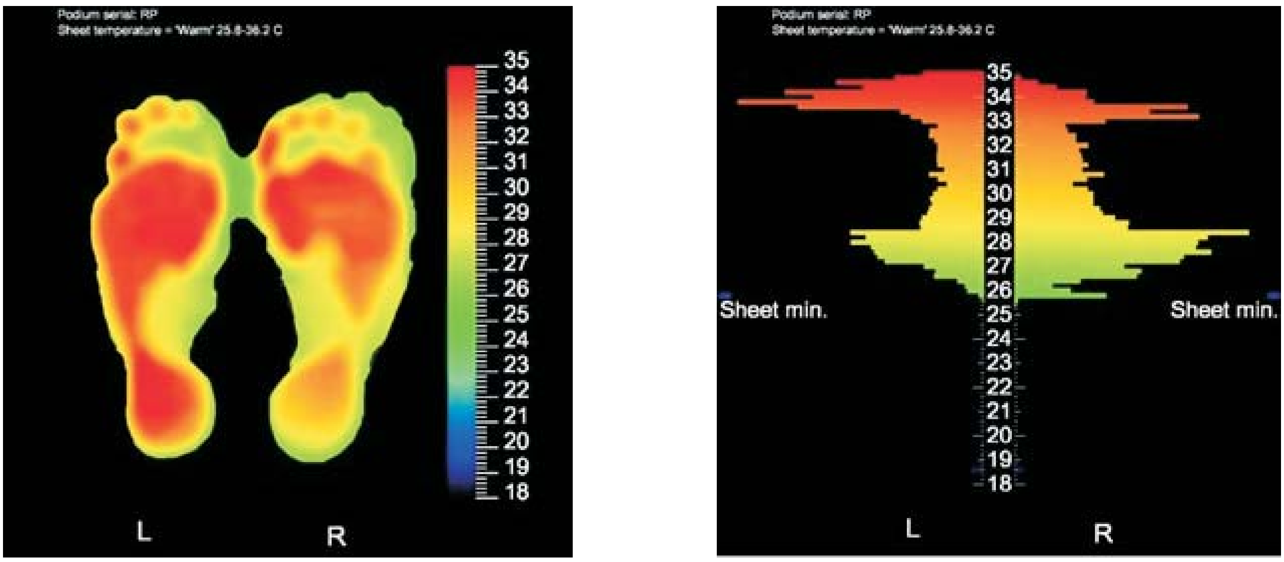


Figure 4:
Thermogram and histogram of a neuropathic diabetic foot

Case Study 1: Neuropathy in Diabetic Feet

Amongst the nerves affected by neuropathy are those of the somatic system over which temperature information is transmitted and the sympathetic fibres that control the thermoregulatory blood flow. The lack of stimulus signals from the impaired sympathetic nerves causes the muscles of the arteriovenous anastomoses (AVAs) to remain permanently relaxed and the AVAs thus being open [12]. These open shunts direct the majority of arterial blood straight into the venous plexus, warming the affected area. Lack of sympathetic nerve signals to the sweat glands also means that the skin cannot sweat. Absence of sweat (and reduced passive transdermal skin wetting through the epidermis in diabetics) contribute further to the higher temperature in the affected areas.

The characteristic features of neuropathy were confirmed in this 57 year old male with poorly controlled type 2 diabetes (more than 10 years) patient with a monofilament test and are visualised in figure 4.

1.**Lack of contralateral symmetry.** Both the thermal image and the histogram show the asymmetric distribution of temperatures between feet.

2.**Medial arch → toe/heel gradient inverted**. In the thermogram of the right foot this is obvious, in the left foot it is not quite so clear but the usually expected gradient between medial arch and toes/heel is certainly very low.

3.Occasional **temperature differences in toes.** Compare the differences between the left and the right first (big) toe.

4.**Extended hot areas**. These are visible both in the thermogram on the left and the large area of high temperatures in the histogram on the right.

5.**Increased average foot temperature**. This is approximately 35°C in the toes to 32°C in the arch area. The histogram shows this typical elevated temperature range, significantly higher than the healthy range between 26°C (toes) and 29°C (arch). This image was taken by a clinician with experience in the thermographic technique and under well controlled conditions. Otherwise this absolute temperature measure would not be a meaningful indicator.

Case Study 2: Navicular Fracture with Background Diabetic Neuropathy

Figure 5 shows the thermogram and associated histogram of a patient who fractured the navicular bone in the left foot 3 months prior to the examination. Increased temperature in the area of the left heel is clearly visible. The clinician noted that due to the pain associated with this injury the patient's gait was atypical with increased pressure being placed on the lateral metatarsals while walking. .

As a result the images show:

1.**Lack of contralateral symmetry.** In particular at the left heel, probably a remnant of the navicular bone fracture.

2.**Medial arch→ toe/heel gradient inverted**. This is partly due to the inflamed areas. However, even when excluding these areas the overall background is still inverted and as such consistent with the patient's neuropathy.

3.**Inconsistent temperature in little toes**. The 2nd toes are colder than toes 3, 4 and 5. Approximately the same temperature would be normal. Such a random pattern is also consistent with neuropathic changes.

4.Both 5th metatarsal head areas are visible as **hot spots** - more pronounced in the right than in the left foot - and likely resulting from the observed changes in gait resulting in excess pressure and friction in these area.

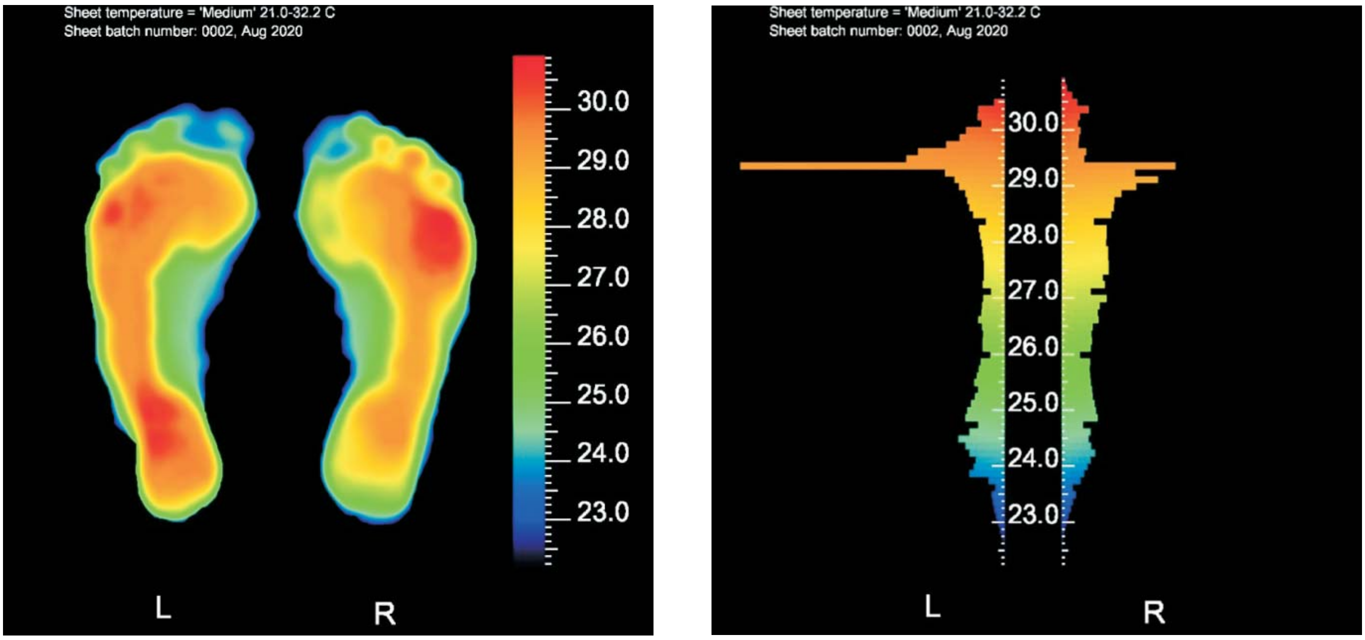


Figure 5:
Three month old navicular fracture in the left foot with background diabetic neuropathy

5.**Overall the feet are warmer than normal.** While this is consistent with neuropathy the clinician's notes show that the examination was made on a hot day in the Summer and in a room without air conditioning. Under such conditions this parameter is of little value.

Figure 5 shows exemplary that the histogram is location agnostic. Notice that the marked asymmetry of the hot areas (red) in the thermogram is not reflected in an equal asymmetry in the histogram because overall the amount of hot pixels in the left and the right foot is approximately the same - just in different places. Conversely, the apparent asymmetry of the single long bar just above 29°C for the left foot is in this instance just a statistical coincidence. A slightly different setting for the histogram's "bucket" temperature boundaries would absorb this spike into neighbouring bars.

Case Study 3: Suspected Macroangiopathy

The patient is a 68 year old male with type 2 diabetes for 3 years. Non-thermal assessment found in the right foot a reduction in pedal pulse with monophasic dorsal pedis & tibial artery flows while in the left foot the flow was still biphasic. On compression the tissue in both feet reacted with blanching, more so in the right than the left. A 10g monofilament test found reduced sensation in both feet. The characteristic features of suspected macroangiopathy are visualised in the images in figure 6. These are:

1.**Lack of contralateral symmetry**. Both the thermogram and its associated histogram show the asymmetric distribution of temperatures between the feet.

2.**Random gradients**. The medial arch to toe/heel gradients are significantly different between the left and the right foot. In the left foot there is only a very small gradient which could indicate neuropathy. In the thermogram of the right foot this inversion is more obvious.

3.**Random temperatures in toes**. Compare the the differences between the left and the right first (big) toe.

4.**Extended cold areas**. These are visible both in the thermogram and the large amount of low temperature values in the histogram.

5.**Average foot temperature significantly below average in affected areas**. The histogram shows that parts of the right foot are significantly below the healthy average range which is between 26°C (toes) and 29°C (arch). Taken under controlled conditions and together with the marked difference between the feet this finding is significant.

In this example the histogram in figure 6 clearly shows the large difference in temperature between the left and the right foot.

Case Study 4: Gout Episode

The series of 3 thermo- and histograms in figure 7 show the feet of a pre-diabetic patient suffering from a gout attack on the day the 1st thermogram was taken. The patient had normal biphasic pulse and good sensory perception (monofilament test) but reported pain in the right foot.

Thermogram and histogram on day 1 clearly show the increased temperature caused by the gout episode. Three days later and following treatment with a non-steroidal anti-inflammatory drug (NSAID) the histogram shows a marked reduction in asymmetry - something that is more difficult to ascertain from the thermogram itself.

On the 5th day the asymmetry is further reduced but an overall large increase in temperature is noticeable. This patient was trained on a Podium Pro device and used it at

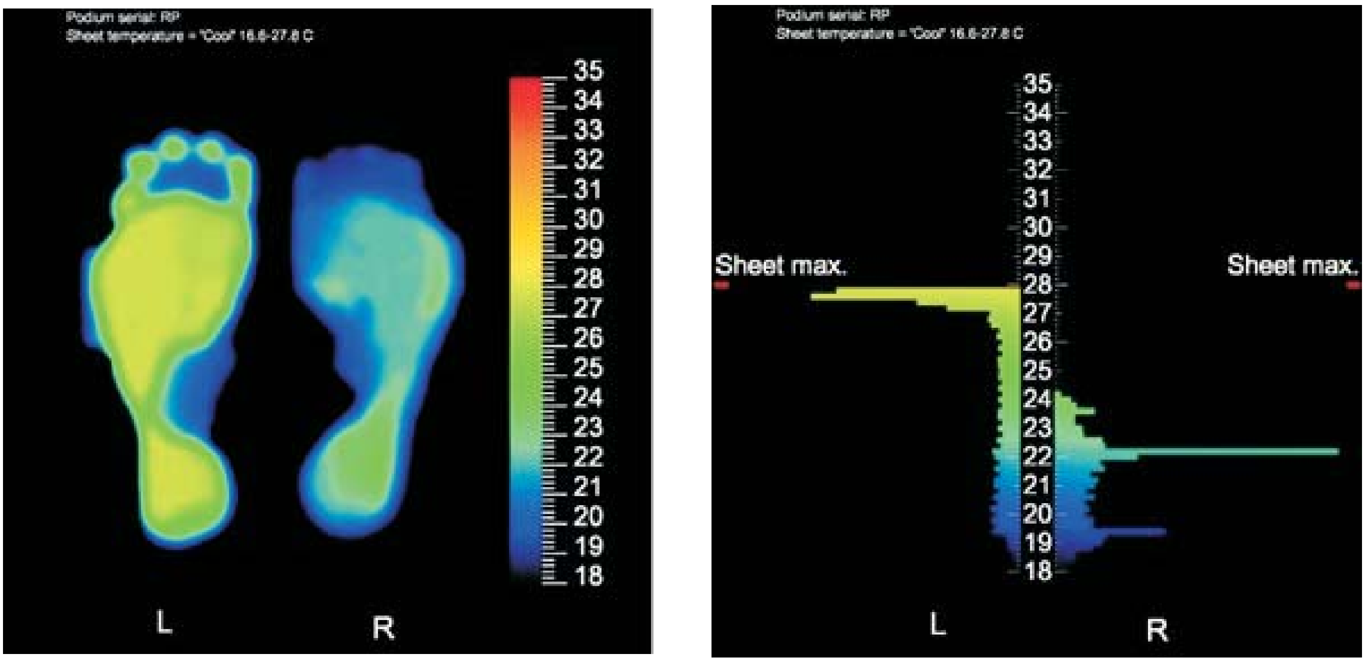


Figure 6:
Suspected macroangiopathy in the right foot

home in his bedroom. Day 5 was a particular hot Summer day with temperatures above 30°C over a 24 hour period and the influence of this is environmental change is apparent.

Discussion

Using thermography or thermal mapping of the foot can help clinicians in several ways:

Educating patients. Thermography is a simple yet immediately intuitive and powerful visual tool for explaining diabetic foot conditions to patients. Better understanding of their own condition may enhance patient compliance and encourage improved and informed self care.

Detecting foot conditions. Thermography can help to detect the onset of particular conditions at an early stage by visualising suspicious temperature distributions that hint at pathological processes [9,13].

Prevention. The earlier a particular problem is detected the higher the chances that further deterioration can be avoided. A suspicious temperature distribution may point early towards a pathological process, which can then be confirmed by established methods of proven diagnostic accuracy [5,8,10].

Aiding treatment decisions. Thermography can be a useful adjunct to locate a problem area and to indicate the direction of further assessment.

Monitoring. The effect of interventions can be visualised to provide an additional indication if a treatment approach is successful.

Using thermography in this way can improve patient care and treatment outcomes. This in turn makes it more likely that patients will remain in primary care without the need for referral to secondary care.

In this paper the authors presented devices and methods for such foot temperature mapping both by clinicians and by patients at home. The devices make thermography of the plantar foot repeatable by encouraging consistent foot placement and consistent visual presentation of results. This can produce meaningful results even under conditions where adherence to a repeatable image capture protocol cannot be guaranteed. First tests demonstrated that the proposed home device is fast and simple to use by patients as part of a daily routine while for professionals a thermal examination with the device as an adjunct is straightforward to include into the workflow of clinical foot assessment without occupying a large amount of time, preparation or technical knowledge. The ability of the devices to send all images to a central server for remote inspection enables a community based approach to patient care, although the logistical challenges associated with this approach remain largely unresolved.

At the moment the analysis of thermograms and histograms is manual and it requires a trained eye to interpret the results, for example to avoid the false impression of symmetry that can be created by the current location agnostic histogram (see case study 2). Further work is needed to create a location aware visualisation of asymmetry.

The device is restricted to the plantar foot. However, due to the small tissue mass the vascular, neurological and inflammatory processes of the entire foot including those from the dorsal aspect tend to leave a thermal imprint on the plantar side.

A limitation of the technique is that some parts of the foot may not be in immediate contact with the liquid crystal sheet. This is usually the medial arch, occasionally also the lateral arch and one or more toes. In the light of the findings by Kluwe [8] and Seixas et al. [14, 15] who locate the highest temperature in the medial arch area the usefulness of the device can therefore at times be restricted.

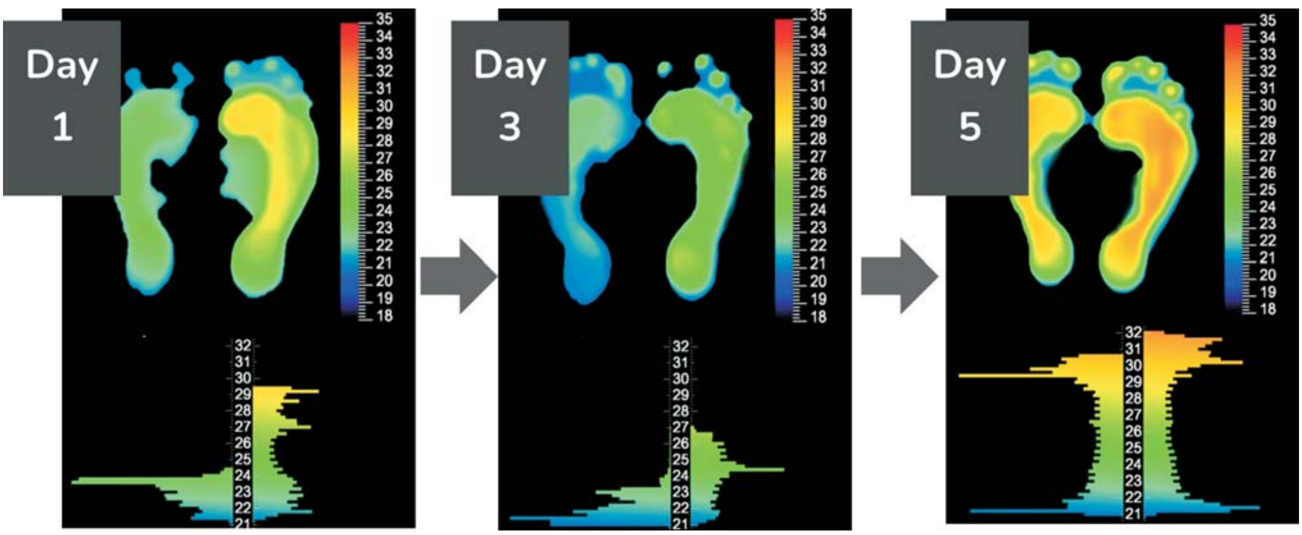


Figure 7:
Follow-up self-administered thermogram series of a patient experiencing a gout episode on day 1. The thermogram on day 3 shows reduced asymmetry following NSAID treatment. Day 5 was a very hot Summer day and its effect on the overall foot temperature is obvious in the thermogram and also the associated histogram that shows a further reduction in asymmetry.

To limit the effect of this factor users are generally advised to apply gentle pressure on these areas to achieve as good a contact as possible. Since the device also captures a visual image the presence of non-touching foot aspects can be established as skin touching the device's carrier plate appears distinctively different from non-touching skin and such areas can thus be taken into account in image analysis. Conversely, deformities such as Charcot foot produce an almost inverted effect where heel, metatarsals and toes might not be in contact with the sheet. In such cases the use of an infrared camera may be more appropriate.

Acknowledgements

The authors express their thanks to all clinicians and patients who helped them to develop the devices. This work was partially supported by the European Community's SME-1 Horizon 2020 program, grant no. 834049.

Conflict of Interest Statement

The authors are employees of Thermetrix Ltd, the company manufacturing and marketing the Podium device discussed in this paper.

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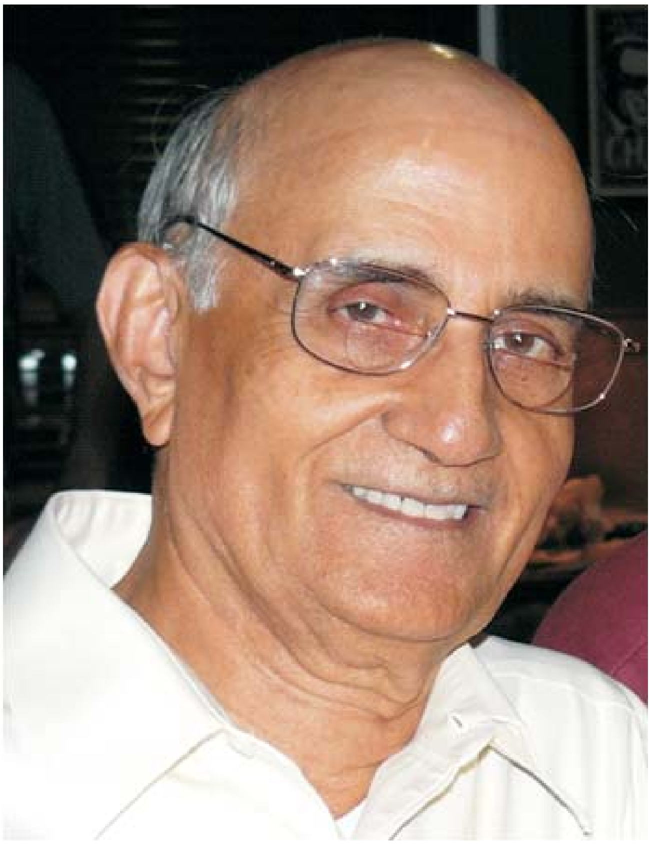

Prof Ram Chandra Purohit PhD MSc

December 15th 1938 to July 5th 2022

It is my sad duty to inform the thermology community that the extraordinary EAT member **Prof Ram Chandra Purohit PhD MSc** passed away on July 5th, 2022, in Auburn, Alabama.

Ram was born on December 15th 1938 in Rajasthan, India. Doctor Purohit joined the faculty at Auburn University as an instructor in 1973 and was promoted to assistant professor in 1974. He was promoted to full professor in 1983. Dr. Purohit earned his BVSc and AH (Bachelor of Veterinary Science and Animal Husbandry) degree from The University of Rajasthan, India in 1962. He did post-graduate work at Washington State University from 1966-1968 in reproductive physiology. Ram completed a PhD at Auburn University in 1974 and a Master of Science at Tuskegee University in 1996. His research interests included thermal imaging, neurovascular thermography, and Thermology of skin dermatomes. Ram had 179 journal publications and four book chapters to his credit. He also gave 112 scientific presentations during his career. He was regular speaker at many national and international Thermology conferences around the world.

Personally, I met Ram for the first time in the year 1990 at the 19th Annual Meeting of the American Academy of Thermology held in New York. Francis Ring introduced me to him and since then I met Ram annually at the Thermology meetings in Europe, USA, or Far East. He visited twice Thermology conferences in Vienna, Austria. Ram was a friendly man with good sense of humour always willing to discuss and explain thermographic findings. I will always remember his discussions with Bill Hobbins about the role of the sympathetic nervous system on the appearance of thermal images.

The Thermology community lost with Ram a pioneer in animal and equine thermology. We will miss him, his vivid presentation and his enthusiasm to teach thermal imaging.

Kurt Ammer,
Editor in Chief Thermology international

I will remember Ram for his energy and enthusiasm for animal thermography, which came across both in his lectures to the EAT, and also in more informal settings during our social occasions. Ram was a true pioneer in animal thermal biology, and had decades of experience and clinical cases that he was always willing to share.

Kevin Howell,
EAT President,
UCL Institute of Immunity and Transplantation,
Royal Free Campus, London, UK

I will forever remember Ram's lively presentations. They always brought a breath of fresh air to every conference session. Unforgettable also the lively discussions with David Pascoe, his Auburn University colleague.

He made us smile and educated at the same time.

Namaste, Ram!

Dr. Peter Plassmann,
Thermetrix, UK

It was through my newfound interest in thermography nearly 25 years ago that I first became acquainted with Ram Purohit. My first meeting with this enthusiastic, knowledgeable and colourful personality was when I attended the 5th International Congress of Medical Thermology combined with the 14th Thermological Symposium of the Austrian Society of Thermology and the Annual Meeting of the German Society of Thermology in Vienna in 2001. At this time, he was already a well-known veterinarian through his work at Auburn University in the USA, especially for his expertise and pioneering work on thermography in horses. He was a member of the Scientific Programme committee for the meeting as well as an active participant. This was my first introduction into the World of thermal imaging and would turn out for me to be the start of a long association with the European Association of Thermology (EAT) and many of its experts in this field. I presented a talk on the comparison of skin temperature changes in the hands and feet of young and elderly subjects following local cooling and was somewhat nervous about my first ever presentation on thermography to an audience of international thermography experts. My nervousness was quickly laid to rest and I was made to feel very welcome into the thermography community by Ram and many other internationally respected experts in equine and medical thermography such as Kurt Ammer and the late Francis Ring, who also attended this congress. As mentioned above little did I know then that my interest in this fascinating field would rapidly grow and I would one day become a President of the EAT. Since 2001 I have met Ram on many occasions in connection with various National and International congresses in thermography. On each occasion Ram was, as ever, a very enthusiastic speaker on topics from his research at the University of Auburn such as equine thermal imaging, neurovascular thermography and the thermology of skin dermatomes. He loved a good discussion both on and off the thermography stage. As I remember on occasions the discussion could become quite heated which added spice to our meetings. As with every scientific meeting the social aspects are enormously important and provide a great way for young and old to become better acquainted. Ram was no exception and was always an entertaining person to be with on these occasions and ever willing to share his expertise along with many amusing experiences from his veterinary career with large farm animals, especially horses. Ram knew everything there was to know about these animals, both inside and out. Through these occasions my wife, Liz, also got to know him and his wife Cynthia. Professor emeritus Ram Purohit, who was 83 years old when he died, was still actively publishing thermographic articles in his late seventies. With his death the thermography community has not only lost an excellent scientist but a warm and friendly person with a charming Indian accent. My wife joins me in sending our sympathies to his wife Cynthia and their family.

Professor emeritus James Mercer, Norway
Past President and lifetime honorary member of the EAT

2023

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The conference, 4th QIRT Asia 2023 will be held in Abu Dhabi, United Arab Emirates

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Contains a session on Medical applications and Covid-19

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- health screening and diagnostics
- veterinary applications.

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Venue: Cape Town International Convention Centre, Cape Town, South Africa

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