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Thermal Imaging as a Noninvasive Diagnostic Tool for Anterior Knee Pain Following Implantation of Artificial Knee Joints

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Abstract

The variety of radiographic diagnostics used to diagnose pain localised close to metal implants is still limited. Especially magnetic resonance results can not be analysed because of artefacts. In this article we present for the first time a direct correlation between an increase in skin temperature and existent frontal (anterior) knee pain after implantation of artificial knee joints measured with thermography.

In a standardised way 26 knees were analysed. Thermographic photos were taken from frontal, inner (medial) and outer (lateral) directions with a computer-assisted infrared thermograph. Temperatures in locations with pain were significantly higher compared to the reference field in inner location (median 0.95 °C, p=0.0043), as well as in outer location (median 0.5 °C, p=0.032). Median temperature difference between pain localization and localizations without pain was 0.7 °C and ranged from 0.1 °C to 1.7 °C. In the receiver operating characteristic (ROC) analysis the sensitivity of this method was 1.0 and specificity was 0.917. The evidence of a significant increase in skin temperature on the painful sites opens up the possibility to localize and assess pain more precisely in patients with joint prosthesis. We consider this novel, rapid, inexpensive and non-invasive technology to posses the potential to become a useful and objective tool for diagnosis of pain and inflammation and to generate digital data that can be stored and analysed in clinical practice.

Keywords: *Thermography; Objective Pain Evaluation; Total Knee Arthroplasty; Anterior Knee Pain.*

Introduction

Noncontact thermal imaging is a valid and reliable measurement of skin surface temperature (Selfe et al., 2006). The history of thermal examination dates back to ancient medicine. It was in the 1940's that the first applicable infrared imaging system for industry and medicine was developed. The first thermal images of the human body were reported in the late 1950's, indicating an increased temperature over arthritic joints (Ring, 2006). A new generation of these instruments arose in the 1970's with the upcoming first computers, allowing imaging storage, processing and analysis of the images as well as colored illustration of temperature patterns. With these systems quantitative thermography was feasible for the first time (Ring, 2004). Modern infrared imaging systems, such as the camera applied in this study, use microbolometer arrays which enable them to detect tiny temperature differences with high speed and spatial resolution. The absorbed infrared radiation changes the ohmic resistance in each image pixel, which can be read out by an amperemeter.

Thus, the kind of camera used in our experiment measures the energy radiated by an object. It needs to be calibrated against a standard black-body, which is an idealized surface in total thermal equilibrium absorbing all impinging radiation.

The spectral radiance $W(\lambda,T)$ corresponds to the radiative energy emitted by a black body. At a certain temperature T this radiated energy depends on the wavelength λ and can be described by the well known Planck's law of black-body radiation (Ng, 2009; Planck, 1901):

$$W(\lambda,T)=\frac{2\pi hc^2}{\lambda^5}\cdot\left(e^{\frac{hc}{k_B\lambda T}}-1\right)^{-1} \tag{1}$$

with h being the Planck constant, c the light velocity and k_B the Boltzmann constant. The energy is given in units of Watts per cubic meter.

In our study we measured this energy with a thermal imaging camera (infrared thermograph). It collects the light being the sum of all emitted wavelengths, therefore integrating over all values of $W(\lambda,T)$, taking into account the sensors wavelength-dependent sensitivity. To reveal the temperature of the measured object, this signal can be directly compared to corresponding data from the calibration record only if the studied object has an emission close to a black-body. The variation from this idealized system is specified by the emissivity, a value between zero and one, with one being for a perfect black-body emitter. Human skin acts almost like such a black-body with an emissivity of approximately 0.98, independent of the skin colour (Steketee, 1973). Thermal imaging is therefore an accurate method to determine the temperature of the skin for medical examination. Modern thermal imaging cameras, like the one we used in our study, perform automatically the described procedure to reveal the temperature.

The peak wavelength of maximal emission in Planck's radiation spectrum for a person can be calculated by Wien's law (Wien, 1896), being at a wavelength of about 9.5 µm in the infrared region. Therefore our thermal imaging system is designed for wavelengths between 7.5 and 13 µm, optimised for the measurement of human temperature.

Thermography, when used in a clinical setting, is a diagnostic imaging procedure that detects, records, and produces images (thermograms) of the patient's skin surface temperatures. In this procedure equipment is used which provides both qualitative and quantitative representations of these temperature patterns. Thermography does not entail the use of ionizing radiation, venous access or other invasive procedures; consequently, the examination poses no harm to the patient (IACT, 2002).

Fairly recent innovations have reduced costs, increased reliability and resulted in noncontact infrared (IR) sensors offering mobile and smaller units for measurement (Brenner et al., 2006; Kastberger and Stachl, 2003). IR thermography visualises characteristic, unusual or pathogenic temperature patterns on the surface of the skin. Areas of increased heat indicate increased blood flow, which can be correlated with inflammation, infection or malignancies. Cold spots show decreased circulation pointing to nerve damage, blood clot or scar tissue (Bruehl et al., 1996; Kastberger et al., 2003; Krumova et al., 2008; Ng, 2009; Rusch et al., 2000; Varju et al., 2004). In the field of veterinary medicine, where localization of pain sometimes is not possible, the IR diagnostic system, used in combination with a clinical examination and additional imaging modalities, provides highly effective results by pinpointing areas of suspicion (Brenner et al., 2006; Craciunescu et al., 2009; Infernuso et al., 2010; Kastberger et al., 2003; Poljak-Blazi et al., 2009; Stubsjoen et al., 2009). In human medicine, thermography has already been effectively used for non-invasive assessment of disease activity in osteoarthritis of the knee, hands and the tempomandibular joint (Boas, 1964; Fikackova and Ekberg, 2004; Salisbury et al., 1983; Selfe et al., 2006; Spalding et al., 2008), as well as in rheumatic arthritis (Boas, 1964; Brenner et al., 2006; Salisbury et al., 1983; Spalding et al., 2008), scleroderma, Raynaud´s disease (Chikura et al., 2010; Schlager et al., 2010), frozen shoulder or rotator cuff tendinitis (Vecchio et al., 1992), breast cancer (Arora et al., 2008; EtehadTavakol et al., 2010; Gescheit et al., 2010; Ng, 2009), reflex sympathetic dystrophy (Bruehl et al., 1996; Krumova et al., 2008; Niehof et al., 2008), sexual dysfunction (Seeley et al., 1980; Smith et al., 2009) and for the evaluation of patellofemoral arthralgia (kneecap pain) in athletes (Devereaux et al., 1986). However, in spite of being a reliable method for objective pain evaluation (Friedman, 1994; Han et al., 2010; Leclaire et al., 1996; Niehof et al., 2006; Pawl, 1991; Pochaczevsky, 1987; Siegel et al., 1987; Zaproudina et al., 2006) it has not been used for pain evaluation following the implantation of artificial joints so far.

Frontal (anterior) knee pain is one of the most common problems after implantation of an artificial knee joint (Skwara et al., 2008) and occurs in approximately 10% of cases (Muoneke et al., 2003). Multiple anatomical structures may be causal of producing anterior knee pain, including the medial (inner) and lateral (outer) retinaculum (ligament on each side of the kneecap), the subchondral bone of the knee cap (patella), the joint capsule, the patellar tendon and the infrapatellar fat pad (fat tissue below the knee cap) (Bennell et al., 2004; Skwara et al., 2008).

The pathophysiological mechanism of anterior knee pain after implantation of an artificial knee joint can have many reasons: an oversized femoral part of the implant, malposition, malrotation, over-forcing of the lateral or medial part of the retinaculum patellae, retropatellar arthrosis, and so on (Barrack et al., 2001; Calvisi et al., 2009; Dalury et al., 2009; Kessler et al., 2008; Mahoney and Kinsey, 2010; Muoneke et al., 2003; Torga-Spak et al., 2004).

Thermography is not a picture of pain. It is a picture of autonomic dysfunction which seems to correlate well with regions of pain (Boas, 1964; Salisbury et al., 1983; Spalding et al., 2008). Pain felt at the area of injury is generally seen to be hyperthermic (increased thermal emission) due to decreased sympathetic function and alpha receptor blockage from metabolic by-products such as substance P, kinins, histamines, and so on (Bjorkstrom and Goldie, 1980; Fernandez-Duenas et al., 2010).

The aim of the study was to evaluate a direct correlation between an increase in skin temperature and anterior knee pain implantation of an artificial knee joint.

Materials and Methods

To reach our aim to assess a follow-up of implanted artificial knee joints, 137 patients responded to an invitation for clinical and radiological control at the authors´ institute. Eight out of these 137 patients (corresponding to 5.8%) suffered from anterior knee pain exactly at the retinaculum patellae and were included in this study. Five patients with anterior knee pain following implantation of an artificial knee joint, who had been operated on in other hospitals, were also included in the trail. Inclusion criteria were pain exactly at the retinaculum patellae following implantation of an artificial knee joint and a pain level of more than 5 in the visual analogue scale (VAS). Exclusive criteria were inflammation, tumour or scars in localization of interest, vascular diseases, nicotine consumption and consumption of non-steroid antiphlogistics or other substances with anti-inflammatory potency. The majority of subjects with anterior knee pain were women (12 female and one male). Mean age was 72.4 years (range from 61 to 84). The mean postoperative time was 3.1 years (range from one year to nine years).

Patients were asked to walk 3 kilometres before entering a room cooled down to 20°C. Following the paper of Selfe et al., visualization without landmarks is not sufficiently reliable, so clinical and anatomic landmarks were identified through palpation (Selfe et al., 2006). The diameter and the distal (lower) margin of the patella were palpated to provide a standardised patient specific method that accommodates for individual anatomy. A black square stripe (thickness 0.7 mm) was attached with adhesive tape exactly positioned under the lower limit of the palpable patella-bone. The horizontal length was the same as the maximal patella diameter; the vertical length was one fifth of the vertical patella length (± 1 cm). Following the International Academy of Clinical Thermology guidelines (2002), patients were asked to remove any clothing covering the lower extremities and subsequently to rest for 20 minutes in order to normalise their body temperature. Then thermographic photos were taken from frontal (0°), medial (45°) and lateral directions (45°), with a computer-assisted infrared thermograph (Thermacam® PM595, Flir Systems, Berchem, Belgium). The infrared camera was positioned 50 cm in front of the knee in all images. Fig. 1 illustrates a typical image, taken from the medial direction showing the mark-stripe, the chosen measure field and the reference field indicated in the picture. These fields were identically positioned in all further thermographic photos, facilitating the comparison of the data. Fig. 2 shows a typical image taken from the frontal direction of a patient with pain in the lateral retinaculum patellae. The thermal difference is well identifiable, although it is generally not recommended to use the frontal view for detecting anterior knee pain (Salisbury et al., 1983; Siegel et al., 1987).

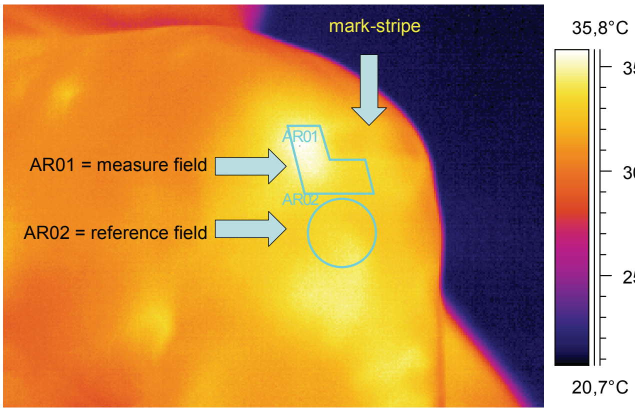


Figure 1. Lateral view of the knee. The black stripe is indicated by a dashed line, the areas referring to the measure field and the one referred to the reference field by solid lines, while the temperature is represented by a colour pattern. (Figure is in color in the on-line version of the paper).

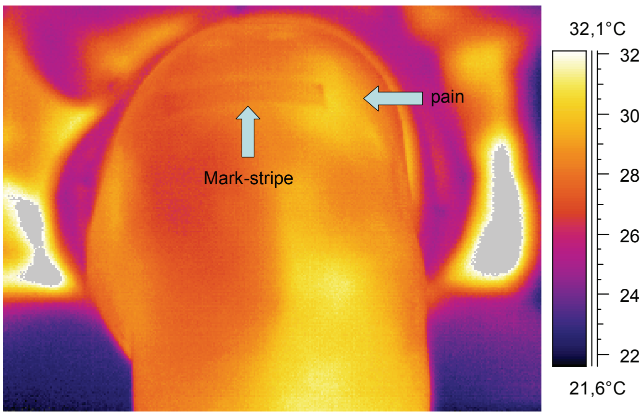


Figure 2. Frontal view of a patient with pain in the lateral retinaculum patellae. The painful area can be clearly identified by the temperature pattern near the mark-stripe. It is not recommended to use the anterior view for detecting anterior knee pain because the patella is acting like a heat shield. However, in this example (patient with pain of the lateral retinaculum patellae) the thermal difference is well identifiable. (Figure is in color in the on-line version of the paper).

The Thermacam® PM595 works in a temperature range from -40 to +500°C and in a spectral range from 7.5 to 13 µm, it has a thermal sensitivity of 0.1°C at 30°C and its measurement accuracy is at least ± 2%. It has an uncooled microbolometer focal plane array with a resolution of 320 x 240 pixels and its internal automatic calibration system uses four temperature references and an automatic emissivity correction. It is adjusted using values in predefined material emissivity tables.

The analysis of the thermographic images was a complex procedure. The temperature difference ΔT was determined between the reference field (AR02 in Fig. 1) and the measure field (AR01 in Fig. 1). Accordingly, all pixels were averaged over values in the corresponding areas. The resulting average temperatures of AR01 and AR02 were then subtracted, yielding a value of ΔT corresponding to each image. Subsequently a statistical analysis for the ΔT-values of different views (lateral and medial) and pain states (pain and no-pain) was performed. We compared the mean value of ΔT of pain localizations with no-pain localizations. Comparisons with the opposite knee were called contralateral, whereas comparisons within the same knee were called ipsilateral.

Statistical Methods:

The distribution of measurements was displayed by box-and-whiskers plots. The whiskers marked minimum and maximum, the box marked the first and third quartile and the horizontal line therein marked the median. Outliers were measurements for which the distance from the box exceeded 1.5 times the interquartile range. Outliers were marked separately and the whisker was only drawn up to the extreme of the remaining values.

Temperature measurements were compared between pain localisations by a two-sided paired t-test. The p-value is a probability lying between zero and one. A p-value close to zero rejects the null hypothesis (no difference between the groups) and a p-value close to one confirms the null hypothesis. P-values smaller than 0.05 were considered to be statistically significant, that means that the null hypothesis is rejected and that there exists a significant difference between the two groups. We used the computer-program R 2.11.0 (www.r-project.org) for statistical computing and graphical visualisation. The area under the receiver operating characteristic (ROC) curve was used to assess the diagnostic value of thermal imaging for pain detection (R package DiagnosisMed version 0.2.3). The ROC curve is a graphical plot of the sensitivity (or true positive rate) versus false positive rate (1 − specificity = 1 − true negative rate). The diagnostic procedure to be assessed was to classify temperature differences below a cut point δ as "no pain" and temperature differences above δ as "pain".

Sensitivity $Sens(\delta)$ was defined to be the relative frequency of pain diagnosis within knee localizations with pain. In a similar manner specificity $Spec(\delta)$ was defined to be the relative frequency of no-pain diagnoses within all pain localizations. For a good diagnostic procedure the functions $Sens(\delta)$ and $Spec(\delta)$ should be as close to one as possible for some values of δ. The ROC curve of a diagnostic test was the diagram of 1- $Sens(\delta)$ against $Spec(\delta)$. The area under the ROC curve (AUC) was a measure of diagnostic performance that did not depend on the choice of cut-point. The highest possible AUC was 1, the lowest possible AUC was 0.5. Smooth ROC curves were obtained by fitting a normal distribution to the data from the pain and no pain localizations. Smooth ROC curves were only used for visualization (see Fig 5).

Results

The median temperature in pain locations (AR01) was 31.2 °C (range: 29.1 to 34.4 °C). Temperatures in pain locations (AR01) were significantly higher compared to the reference field (AR02) both in the medial location (median ΔT 0.95 °C, p=0.0043) as well as in the lateral location (median ΔT 0.5 °C, p=0.032). Within all pain locations the median ΔT was 0.7 °C and ranged from 0.1 °C to 1.7 °C on the side of the pain (Fig. 3).

The comparison of ΔT on the ipsilateral knee (comparison of two localizations on the same knee, i.e. ΔT medial side of pain knee to ΔT lateral side of the same knee) is visualized in Fig. 3. The median of the differences of ΔT between pain and ipsilateral no pain locations was 0.9 °C and this was statistically significantly different from zero (p=0.0000026).

Median absolute temperature on the contralateral side was 31.05 °C. Comparison of pain ΔT (difference of AR01 minus AR02) with the contralateral ΔT (same localization on the other pain-free knee) gave a median difference of 0.8 °C which is also significantly different from zero (p=0.0036) (Fig. 4).

The performance of thermal imaging as a diagnostic test for pain location was assessed by ROC analysis (Fig. 5). With the ipsilateral procedure an AUC of 0.98 was obtained. If the cut point is just below 0.1 °C, sensitivity is 1 and specificity was 0.917. If the cut point was chosen to be just above 0.1 °C, sensitivity was 0.875 and specificity was 1. For the comparison with the contralateral location the diagnostic performance is worse (Fig. 5).

As expected, in pain-free localizations there were no statistically significant differences between measure (AR01) and reference field (AR02) (medial: p=0.18; lateral: p=0.12; temperature differences from -1.1 °C to 0.9 °C). The median ΔT was 0.0 on the medial side and -0.1 on the lateral side.

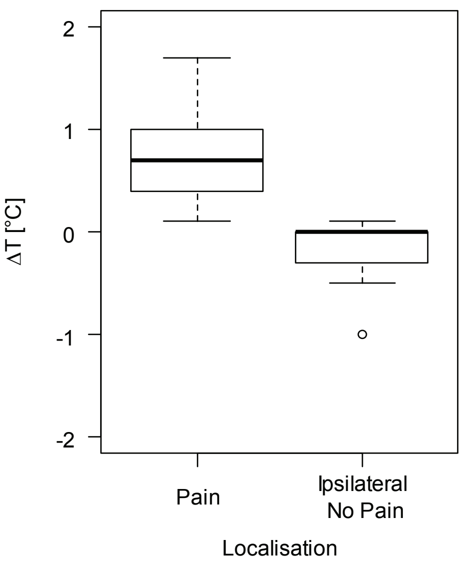


Figure 3. ΔT (temperature at localization of the retinaculum patellae [AR01 in Fig. 1] minus temperature at the reference point) of pain localization (lateral and medial) and painless localization on the same (ipsilateral) knee (AR02 in Fig. 1). Data were only taken from 45° view.

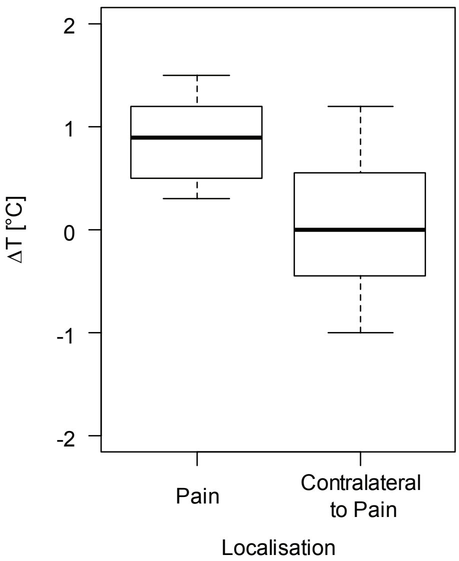


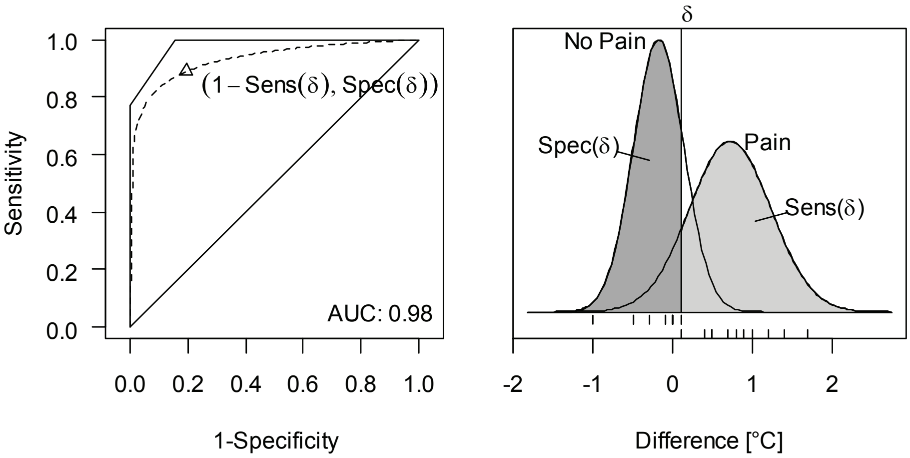
Figure 4: ΔT from pain knees and the same location on the other (contralateral) knee without pain. Data were only taken from 45 degree view.

Discussion:

Thermal imaging proved to be an effective tool for diagnosing inflammation and pain. However, it never had been tested to evaluate pain syndromes after implantation of artificial joints. So this is the first study in which thermography is used to determine pain after implantation of artificial knee joints correlating with temperature differences. We have demonstrated that there is a significant correlation between anterior knee pain and an increase of superficial skin temperature around the anatomic localization of the retinaculum patellae. Sensitivity and sensibility of comparing pain localization with the other retinaculum side (e.g. medial with lateral) of the same knee showed to be superior than comparing with the contralateral knee because of less variability. We suspect that the reason for this observation is that the operated knee has a different temperature than the not operated. On the one hand the implant could act as a heat shield and decrease the superficial measured temperature, while on the other hand postoperative inflammation and irritation could provoke an increased temperature.

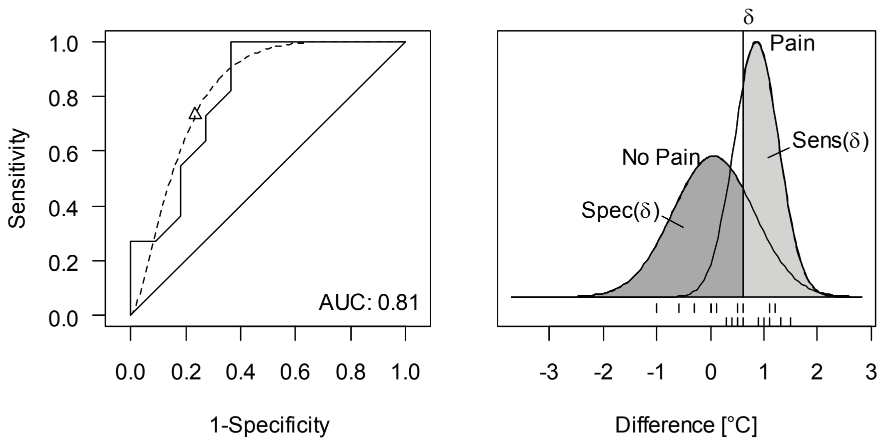
Our results confirm observations by previous investigators concerning the increase of temperature with pain around limbs. Deveraux (Devereaux et al., 1986) for instance has demonstrated that athletes with patellofemoral arthralgia showed an increase of temperature in the anterior and medial view medially beside the patella, corresponding to the site of tenderness. Of 30 athletes, 28 showed this pattern in the painful knee. Two patients with pain had no elevated temperature in the thermogramm. All patients were asymptomatic at a three month follow-up after having undergone treatment with physiotherapy and electric stimulation and the heat abnormalities noted on thermography had disappeared (Devereaux et al., 1986).

Varjú et al. assessed 91 subjects (2184 joints in total) with nodal hand osteoarthritis (OA) and found that the joint surface temperature corresponded with the severity of radiographic osteoarthritis. They supported moreover that thermography may provide a sensitive tool to followe the response of digital OA to disease modifying agents (Varju et al., 2004).



(a) (b)

Ipsilateral difference of temperatures



(c) (d)

Contralateral difference of temperatures

Figure 5: ROC analysis of diagnosis of pain through differences of ΔT with either ipsilateral locations in (a) and (b) or contralateral locations in (c) and (d). In (b) and (d) normal densities were plotted above tick marks of observed differences in order to visualize how by means of a cut-point δ a certain proportion of correct pain diagnosis (sensitivity, dark shade) and correct no pain diagnosis (specificity, light shade) was obtained. In (a) and (c) ROC curves from observed data (continous lines) and from the fitted normal densities (dashed lines) were plotted. The AUCs referred to the ROC from the observed data. δ was 0.1 in (a) and (b) and δ was 0.6 in (c) and (d).

Spalding et al. assessed patients with rheumatic arthritis with standardised thermographic methods. He defined the Surface Distribution Index (SDI) as one standard deviation from the mean of all surface points-to-bottom plane distances and evaluated the Heat Distribution Index (HDI) as twice the SDI of all temperatures within a predefined region of interest. In addition to that he suggested that thermal surface imaging could be used to improve the assessment of disease activity in arthritis and could quantify clinically meaningful changes in arthritic joints in response to therapy. Finally he suggested that a HDI of greater than 1.3 °C could be used to identify patients with active arthritis with a sensitivity of 67% and specificity of 100% (Spalding et al., 2008).

Our study demonstrates that temperature elevation is sensitive for the localization of pain, when a temperature difference of 0.1 degree in ibsilaterale sides was measured. If the cut-point is just below 0.1 °C, sensitivity is 1 and specificity is 0.917.

Siegel et al. used computerised thermography in the evaluation of non-traumatic anterior knee pain. They examined eight patients with anterior knee pain with a Dorex Computer-Aided Thermography System (Siegel et al., 1987). They did not find any correlation between increase or decrease in pain and increase or decrease in temperature and suggested that the patella may act as a heat shield, therefore creating a cold patella thermal pattern such as Salisbury et al. had found before (Salisbury et al., 1983). Siegel et al. only used frontal views and therefore later recommended to use lateral views to minimise the cold patella effect. In our study as well the frontal view for detecting anterior knee pain could not be used.

An incidence of 10% of anterior knee pain following implantation of an artificial knee joint has been published (Muoneke et al., 2003). Recently, much attention has been directed to femoral component overhang and also femoral component malrotation in artificial knee joints (Berend et al., 2010; Classen et al., 2010; Ghosh et al., 2010; Gravius et al., 2010; Mahoney et al., 2010; Moon et al., 2010; Popovic and Lemaire, 2003; Verlinden et al., 2010). The variety of radiographic tools used to help diagnose pain localised close to metal implants is still limited. Especially magnetic resonance result can not be analysed because of artefacts. Therefore, new techniques for visualising pain after implantation of artificial knee joints are necessary.

Furthermore, differentiation between organic and functional pain is important during the diagnostic process of painful artificial knee joints. Tests performed at these anterior knee patients revealed a complex problem which is not only somatic, but also of psychological nature (Witonski, 1999). Furthermore thermography appears to be a method which helps to visualise pain and could be used for verifying a somatic problem, especially in patients suspected of having psychosomatic disorders.

Conclusion

Anterior knee pain is a common problem following implantation of artificial knee joints. Measuring the temperature differences by thermography could contribute to help localising and assessing pain more precisely. In our study we verified a significant increase in skin temperature on the painful site of patients suffering from anterior knee pain after implantation of artificial knee joints. The new generation of thermal imaging techniques has significantly improved resolution and temperature sensitivity and generated reproducible measurements of surface areas. We consider this novel, rapid, inexpensive and non-invasive technology to have the potential to become a useful tool to objectify pain and inflammation while simultaneously generating digital data that can be stored and compared in daily practice.

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Authors contributions:
The authors have no conflict of interests with regard to this work. No author is a shareholder or consultant for Flir Systems, Berchem, Belgium Inc. All authors read and approved the final manuscript.

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