Infrared thermal imaging as a screening tool for paediatric wrist fractures

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Infrared thermal imaging as a screening tool for paediatric wrist fractures

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Abstract

Wrist injuries are common in paediatric trauma, however only half of children evaluated with an x-ray for possible fractures will have one. Thermal imaging offers a possible non-ionising method of screening for fractures and thus reducing negative x-ray rates.

105 children attending the Emergency Department for wrist injuries were recruited. Two 30s thermal videos were recorded from injured and uninjured wrists – in flat and 45^{o} elevated positions. A region of interest (ROI) was defined on each wrist. Cases in which the ROI was covered or had ice applied, were excluded, leaving 40 patients for analysis. Comparisons of ROI included (i) injured and uninjured wrists - flat and elevated positions; (ii) as in (i) with a reference region on the proximal forearm subtracted; (iii) injured wrist ROI - flat and elevated positions.

Fractures and sprains increased the mean skin surface temperature by 1.519% (p=0.008) and 0.971% (p=0.055) respectively compared with the uninjured wrist. The mean temperature difference between flat and elevated positions for fractures was 0.268% and -0.1291% for sprains. This difference was statistically significant for fracture (p=0.004) but not sprain (p=0.500).

The temperature differences recorded by thermal imaging between fractured and sprained wrists may assist in differentiation of these injuries.

Keywords Thermography, Wrist injuries, Sprain, Bone fracture, Paediatrics

1 Introduction

Acute wrist injuries are a common presentation to paediatric Emergency Departments (EDs). Differentiating a fracture from no fracture (the latter referred to as a sprain in this article), can be challenging based on history and physical examination alone. Diagnostic x-ray is usually performed when a fracture is suspected in as many as 91% of children presenting with a wrist injury (van den Brand et al., 2013). Around 50% of these x-rays fail to demonstrate a bony injury (Slaar et al., 2012).

X-rays are a source of ionizing radiation, which can cause potentially carcinogenic damage to DNA (Lin, 2010). Furthermore, children are at even greater risk of the damaging effects of x-ray than adults

(Davies, Wathern and Gleeson, 2011). Guidance on the clinical use of x-ray therefore mandates that exposure to ionizing radiation should be minimised as much as is possible (The Council of the European Union, 2014, Gogos et al., 2003). In addition, there are unjustified costs associated with staff, radiology and patient excess time when x-rays show no underlying bony injury.

Fractures are very common in the paediatric population with 42% of boys and 27% of girls suffering at least one fracture before the age of 16, with a peak incidence during adolescence (Landin, 1983).

Fractures of the distal radius, the most commonly fractured bone of the wrist in children, account for 25% of all paediatric fractures (Nellans, Kowalski and Chung, 2012). Combined with fractures of the metacarpals and phalanges, these account for 50% of all paediatric fractures (Nellans, Kowalski and Chung, 2012). When a fracture occurs, the underlying physiological processes taking place lead to changes in skin surface temperature at the site; these changes may be measured using thermal imaging (Silva et al., 2012, Sanchis-Sánchez et al., 2015, Fane De Salis, Saatchi and Dimitri, 2018, Ćurković et al., 2015, Haluzan et al., 2015). Considering the high prevalence of wrist injuries and high proportion of x-rays which report negative findings, a screening method to assist clinicians decide whether an x-ray scan would be needed would be beneficial.

A fracture results in a disruption to vascularisation and an acute inflammatory response. These physiological processes and those associated with the various stages of fracture healing lead to temperature changes within the tissues, measurable from the skin surface at the site of the injury (Silva et al., 2012, Sanchis-Sánchez et al., 2015, Ćurković et al., 2015, Haluzan et al., 2015, Fane De Salis, Saatchi and Dimitri, 2018). Fractures have distinguishing physiological processes that may affect skin temperature and a pattern which allows distinction from a sprain (Baoge et al., 2012). By definition, a sprain is an acute injury, causing damage to one or more ligaments in a joint. The damage can range from overstretching of the ligament to a complete tear or rupture, causing complete loss of function and requiring surgical intervention (NICE, 2016, Leversedge, 2018). When a sprain occurs, the symptoms are similar to those in fractures, with swelling and increased temperature at the site. The injury and healing processes are grouped into three stages: the destruction and inflammatory stage, the repair stage and the remodelling stage. Though these stages bear similarities to those occurring in fractures and fracture healing, they tend to occur over a much shorter time period: 1-3 days, 3-4 weeks and 3-6 months respectively (Baoge et al., 2012). Additionally unlike fracture healing, there is no callus formation in the repair phase and there is instead the regeneration of any damaged myofibres, and the formation of fibrinous scar tissue, which is eventually reorganized in the remodelling phase (Baoge et al., 2012). Often when damage has occurred to the wrist and no fracture is revealed on diagnostic radiology, this would commonly be referred to as a wrist sprain, even though standard x-ray would not provide objective evidence of damage to the ligaments. For this reason, all non-fractured wrist injuries in this article are referred to as a wrist sprain.

Infrared thermography (IRT) or thermal imaging (TI) is a harmless technology that detects infrared radiation emitted from the skin, which is related to peripheral blood flow and perfusion (Ring and Ammer, 2012) (Alkali et al., 2017) (Lahiri et al., 2012). Given IRT's ease of use, portability and non-contact and non-ionising features, it may be particularly beneficial in the paediatric population (Owen and Ramlakhan, 2017). The aim of this study is to investigate the presence of significant temperature differences between a wrist fracture and sprain, and whether these differences allow differentiation of the two injury types. The tests performed compared the temperature of an injured wrist (fractured or sprained) with the contralateral (uninjured) wrist region of interest (ROI) on the same patient when the hands were in flat and elevated (to 45^{o}) positions. A further comparison tested the temperature of the injured wrist in flat and elevated positions. The hypothesis related to including the tests in elevated hand position was to explore whether the gravitational effect may alter the vascular and extracellular fluid's perfusion at the site of injury in a manner that could cause distinguishing temperature difference measurable by thermal imaging. There were no previous studies to our knowledge specifically exploring the effect of gravity on blood perfusion at the site of fracture and sprain; however, there were studies exploring the influence of the position of the limb and gravity on the measurement of blood pressure. These studies indicated a reduction in blood pressure (and hence perfusion) in the arm when it is elevated (Martin-Du Pan, Benoit and Girardier, 2004).

In the following sections, a literature review of studies related to the application of thermal imaging in fracture detection and healing is provided.

2 IR Thermal imaging in fracture healing and fracture detection

A study by Haluzan et al. (2015) was one of the first to use thermal imaging to measure the temperature changes taking place during normal bone healing. The temperatures of the distal radius of fractured and healthy forearms in 25 adult patients and were measured with the difference between the two calculated. They found an increase in skin surface temperature of the fractured wrist in comparison to the uninjured wrist, at different times during fracture healing. In comparison to the uninjured wrist, the temperature of the fractured wrist was higher between 1 to 11 weeks post-injury, with a peak increase in temperature occurring at 3 weeks post-injury. Relating these observed differences to the stages described above, it can be inferred that at 1week post injury, the acute inflammatory response is concluding and the reparative phase is beginning, angiogenesis and cartilaginous callus formation are taking place, causing an increase in temperature at the fracture site. At 3 weeks post-injury the microvascular invasion and perfusion to the fracture site is at its highest as the cartilaginous callus is vascularised before ossification, causing the greatest increase in temperature. At five weeks, the callus is beginning to calcify and the temperature begins to decrease. By week 11, the ossification of the callus has continued and the temperature difference is further decreased until 23rd week, when the remodelling process will be underway and there is very little difference in temperature between the injured and uninjured wrist (Haluzan et al., 2015).

TI was used to monitor skin surface temperature changes during fracture healing within a paediatric population (Ćurković et al., 2015). Nineteen children aged 4 to 14 years who had sustained forearm fractures had TI of the fractured and uninjured wrists at 7, 14 and 21 days post-injury. Temperature difference between the fractured and uninjured forearm was greatest 7 days post-injury, had decreased at 14 days post-injury and was minimal at 21 days post-injury. This is reflective of the underlying stages of fracture healing taking place. Where this study found the greatest temperature difference to be at 1 week post-injury, Haluzan et al. (2015) found this peak to be at 3 weeks post-injury. One explanation for this difference could be that the study by Ćurković et al. (2015) was assessing the temperature difference measured in children in whom the processes of microvascular invasion and fracture healing occur more quickly than that in adults due to increased vascularity (Ćurković et al., 2015).

An exploratory study by Silva et al. (2012) aimed to evaluate the use of TI in matching the area of pain and in accurately detecting fracture sites in cases of paediatric extremity trauma. They recruited 51 children who were to undergo radiographic imaging for fracture diagnosis. In addition to x-ray imaging, TI was performed and the results of the two approaches were compared. TI accurately matched the area of pain in 73% of patients, however it only matched 7 of the 11 fracture sites (64%).

Sanchis-Sánchez et al. (2015) investigated the potential of TI as a tool for ruling out fractures in a paediatric ED. They recruited 145 children who had sustained a traumatic injury and were undergoing diagnostic x-ray. TI had a sensitivity of 91% and specificity of 88% in detecting fracture. Additionally, a negative predictive value (NPV) of 95% was reported. The high NPV led the authors to conclude that TI was effective in ruling out paediatric fracture in emergency trauma cases.

Fane De Salis et al. (2018) evaluated whether TI could be used to detect skin surface temperature (SST) changes over vertebral fractures in children with osteogenesis imperfecta (OI). They aimed to assess whether TI might then be used as a complementary monitoring tool for vertebral fracture detection in these patients. The study enrolled 11 patients between the ages of 5 to 18 years with a diagnosis of OI and vertebral fractures. Metal discs were placed on the skin alongside the vertebrae of the patient as a marker and dual energy x-ray absorptiometry (DXA), x-ray imaging and TI were performed. A temperature percentage change (TPC) was calculated by comparing the SST above the fractured vertebra to an adjacent reference region with the SST above a non-fractured vertebra. The study reported the TPC between the SST over the fractured thoracic vertebrae and the reference region to be statistically significant (1.44%, $p=0.002$) but not so between the healthy vertebrae and the reference skin region (0.97%, $p=0.15$).

Owen et al. (2017) evaluated the use of IRT as a diagnostic tool for acute undifferentiated limp in young children. They recruited 30 patients and amongst them, there were three patients with fracture. The study gives an exemplary case in which IRT was able to detect a ‘hotspot’ on imaging, when there was no pathological finding on initial x-rays. A subsequent x-ray two weeks later retrospectively confirmed the diagnosis of toddler’s fracture. This highlights that TI may have the potential to detect fractures before they are detectable on radiographic imaging, however further investigation with a larger sample size would be required to confirm this concept.

3 Methodology

3.1 Ethical issues and study setting

A favourable ethical opinion was attained from the Sheffield NHS Research Ethics Committee (NREC) (IRAS project ID: 253940). Dedicated patient information sheets for children and carers were used to provide details of the study's purpose, procedure and the patients' rights. Informed assent (for children) and consent (for carers) were obtained prior to the recordings taking place. The patient information and recordings were anonymised prior to storage and processing in accordance to the Data Protection Act (2018).

Recruitment took place from an urban tertiary paediatric ED. A dedicated procedure room close to the x-ray imaging laboratory was chosen where all TI took place. The room was free of heat sources that could have affected the accuracy of imaging. There was a window but this did not open and was sealed and obscured, minimising draught. As the same room was used for all recordings, the room temperature variations between recordings were minimal and conformed with the recommendation to be within the range of 18 to 25 ^{O}C (Ammer and Ring, 2012).

3.2 Recruitment

The study aimed to recruit an equal proportion of males and females, between the ages of 5 and 15 years, who would be undergoing a diagnostic wrist x-ray for wrist fracture. Altogether 105 patients were recruited. The exclusion criteria were:

- Non-native English speakers or those unable to understand the study procedures.
- Children with multiple injuries or an obvious deformity to the wrist.
- Children in significant pain (triaged above category D due to pain or deformity).
- Children who had not assented, on whose parent or guardian had not consented.

3.3 IR Thermal image acquisition

Video recording was considered advantageous over still images as a method of measuring skin surface temperature as it allowed pixel values within the region of interest (ROI) to be averaged both spatially and over time. Temporal averaging further reduced thermal noise and possible temperature fluctuations that may occur over time. Patients were allowed to acclimatise to the recording room temperature for 10 minutes. Two 30-second videos were taken, one with the forearm placed in a flat position on the table and the second with the hands placed on a 45^{O} elevated stand (Figure 1). For both positions, the camera was perpendicular to the forearm long axis. The image capture rate was 30 frames per second (30 Hz).

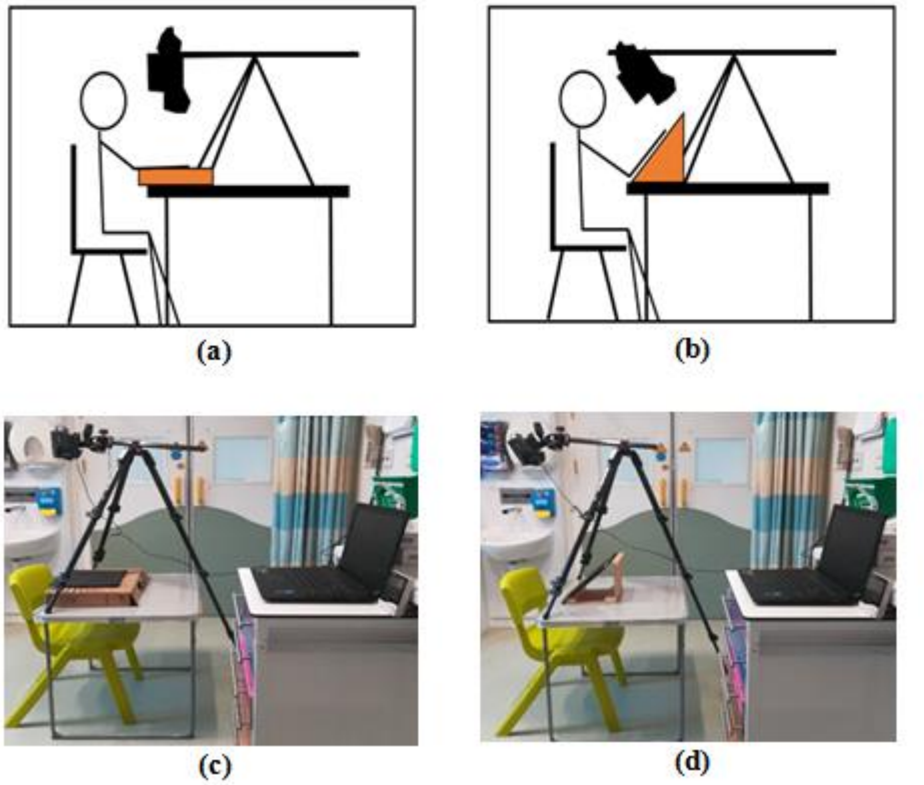

Figure 1 (a) and (b) schematic representations of the data recording arrangement for the wrists in flat and 45^{o} elevated positions respectively. The camera (in black) was connected to a computer. The camera tripod allowed folding as shown. (c) and (d) are photos of actual set ups for (a) and (b).

In order to reduce heat flow between the hands and their supporting platform during recording, a number of different insulating materials to cover the surface were thermally tested. Ideally, in TI the area being imaged should not be in contact with other surfaces as this causes heat flow to move between the objects via conduction (Ammer and Ring, 2012). Several foam materials were tested by placing hands on them and observing the heat interaction through TI. The foam that provided the least heat transfer was selected and used for all recordings.

Prior to TI taking place, the patient's age, weight, sex and the wrist that had been x-rayed (i.e. injured wrist) were recorded. The outcome of x-ray diagnosis (fractured, sprain) was obtained from the hospital records. Temperature and humidity of the recording room were recorded. The patient was asked a series of questions:

- Date and time and injury
- Any medication taken and if so when.
- The manner injury occurred and whether they had pain in the uninjured wrist.

Following TI, the patient’s body temperature was recorded using a tympanic thermometer. A number of patients had applied ice to the injured wrist prior to attending hospital. The application of ice affected the recorded skin surface temperature of the wrist ROI, as demonstrated in Figures 2(a) and 2(b). In Figure 2(a), the left wrist was fractured; ice was removed from the wrist 15 minutes prior to imaging. In Figure 2(b) the left wrist was also fractured; ice was removed from the wrist 6 minutes prior to imaging.

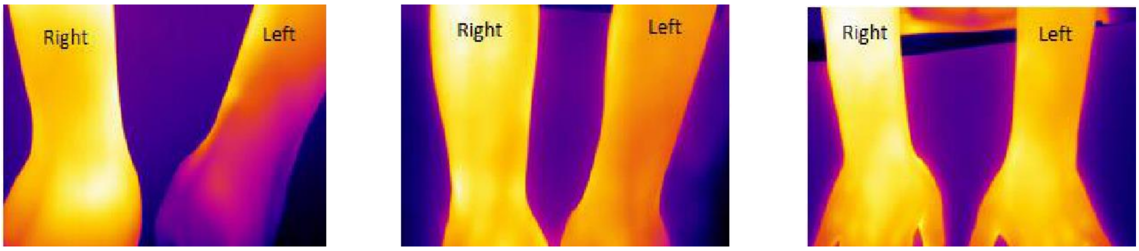

Figure 2 The effect of ice and sleeves on the thermal images of patients with (a) left wrist fracture, ice applied for 105 minutes and removed 15 minutes prior to imaging. (b) as in (a) but but ice has been applied to the left wrist for 109 minutes and removed 6 minutes prior to imaging. (c) the left sleeve was removed 15 minutes prior to imaging and the right sleeve removed 5 minutes prior to imaging. Darker colours represent relatively cooler regions.

The application of ice caused the fractured wrist to appear cooler, as indicated by darker colours in Figures 2a and b. The effect of ice application on the diagnostic accuracy was not considered in the scope of the current study and so the patients who had ice applied to the injury site were excluded from analysis (the excluded patients will be studied in further work to explore the manner in which ice affected diagnostic accuracy for TI). Some patients had articles such as long sleeves or slings covering one of the wrists. This also affected the recorded skin surface temperature. Figure 2(c) shows the wrists of a patient who had fractured their left wrist and had sleeves removed from the left and right wrists 15 and 5 minutes respectively prior to TI. The right wrist appears warmer than the left. Patients in whom an article had covered either wrist during the acclimatisation period were excluded but will also be analysed in further work to establish the extent of discrepancy this can cause in the diagnosis. Following these exclusions, 40 patients (19 with fracture, 21 with sprain) remained and were included in the current analysis. Some medications can affect body temperature (Murphy, Myers and Badia, 1995). For this reason, it was also recorded whether the patient had taken any analgesia, either at triage or before attending the department. The dosage and route were recorded as well as the time since the medication was taken.

3.4 Equipment, software and image processing

The thermal camera used in this study was the FLIR T630sc handheld camera (FLIR® Systems Inc, West Malling). This has a temperature sensitivity to within 40 mK, image resolution 640×480 pixels, spectral range 7.5 µm to 13 µm, dynamic range 14 bits and operating temperature -14 ^{o}C to 50 ^{o}C. The camera was connected to a laptop for data storage. The thermal videos were processed and analysed in Matlab© (version 2017, Mathworks Inc, Cambridge).

3.5 Comparing the difference in temperature (ΔT) between wrist fractures and sprains

Three tests were performed to investigate any temperature differences between wrist fracture and sprain. These were:

- Test 1: This compared the temperature of the injured wrist (fractured or sprained) with the contralateral uninjured wrist in the same patient. This test was repeated, once with both hands in a flat position and then with both hands 45^{o} elevation.
- Test 2: As in Test 1 but a proximal region of the ipsilateral arm was used as a reference to account for possible baseline *T* between the wrists, i.e. a *T* that may exist between the two wrists, not associated with the injury. A study by Vardasca et al. (2012) found the temperature difference between the upper extremities in healthy subjects to be as large as 0.5±0.3 ^{o}C. Furthermore, a study by Gatt et al. (2014) found that the temperature difference between corresponding anatomical sites to be less than 0.89 ^{o}C. Given that there may be temperature differences between the upper limbs, the purpose of this test was to explore compensating for this possible temperure difference by subtracting a reference region of the forearm from the temperature of the ipsilateral wrist ROI.
- Test 3: Compared the temperature of the injured wrist in the flat and 45^{o} elevated positions (the uninjured wrist was not used in this test).

The wrist ROI was selected to include the carpal bones and the distal radius and ulna. The selection was based on anatomical landmarks and involved displaying the thermal image of the patient's wrists using Matlab©. An area was selected to capture the region where injuries are expected; the perpendicular distance between the radiocarpal joint (RCJ) and the base of the metacarpals (MC) was taken distal to the RCJ (*RCMC*), with a perpendicular distance equivalent to 1.5 x *RCMC* proximally. The total axial length of the ROI on the image was then established by the ratios 1:1.5 centred on the RCJ to select the ROI, these ratios are illustrated in an x-ray image (Figure 3).

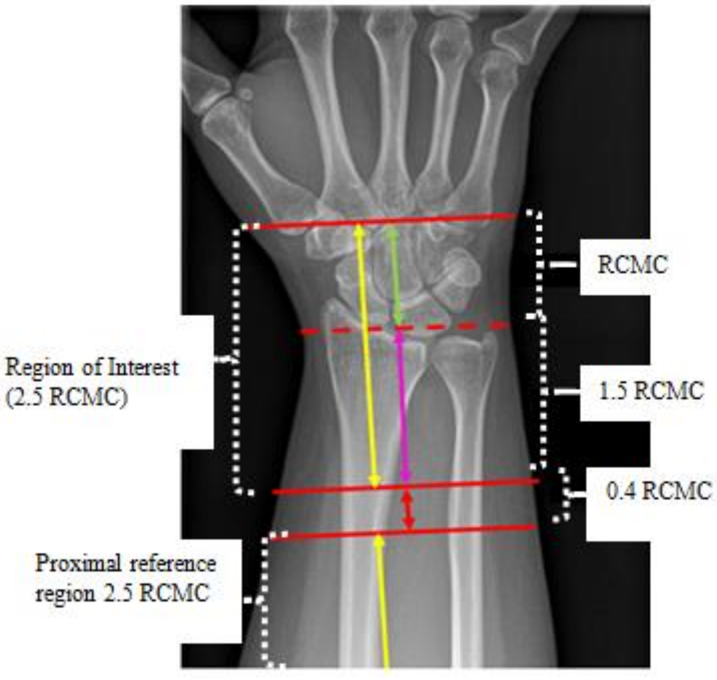

Figure 3 A schematic representation of the ratios used to determine dimensions of the wrist and forearm ROIs.

The ROI for the ipsilateral forearm used as the reference for test 2 was selected on the image to be the same perpendicular (axial) length of the calculated wrist ROI, from a distance of 0.4 RCMC from the proximal boundary of the wrist ROI.

Four ROIs were selected for temperature measurement: left and right wrists and left and right forearms. The ROIs were delineated by displaying the first image, and assisted with the relevant Matlab© functions, manually drawing the contour of the ROI as shown in Figure 4. Once the ROI was manually delineated in the first image, its delineation in the following images was automatic and was achieved through the tracking algorithm described in the next section.

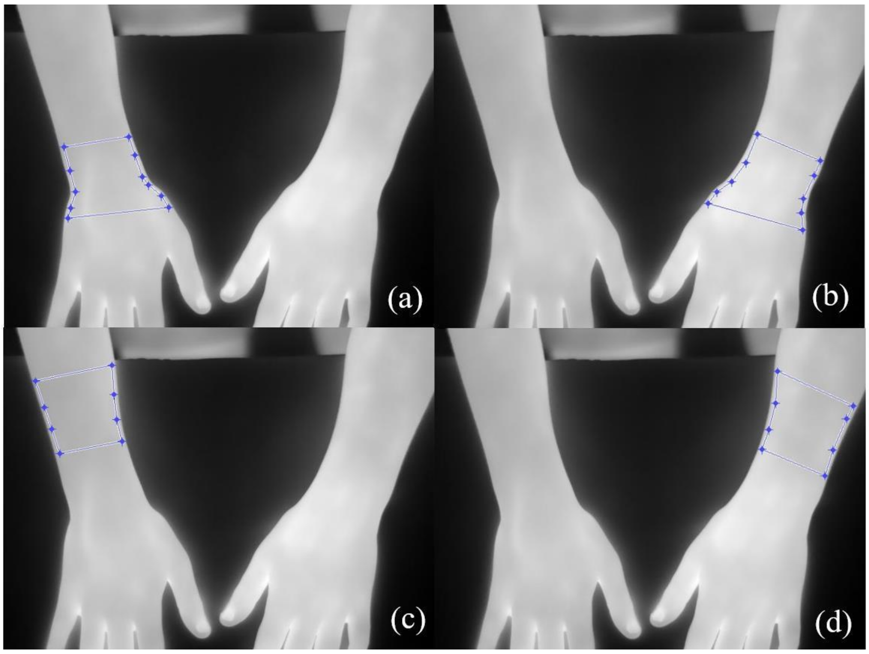

Figure 4 Representation of the four ROIs selected in the flat position (a) right wrist (b) left Wrist (c) right forearm (d) left forearm.

3.6 Tracking the ROI

Once the ROI from the first image was selected, the same region had to be identified across all the images within the image recording. As there were the possibility of slight wrist movements, a ROI tracking algorithm was needed to ensure an identical region was selected in all images. A template-matching tracking method (Brunelli, 2009) was applied to align the ROI being processed, across all images within the video. The identified ROI in the first image acted as the template. This template was matched in each of the subsequent images, the region in the image that provided the highest correlation to the template was selected as the ROI in that image.

3.7 Representation of ROI by statistical parameters

Figure 5 shows the stages in representing the ROI by statistical parameters. The selected ROI across the images for a video were averaged to generate a single mean ROI. For Test 1, this was performed for both wrists, for Test 2, it was repeated for both wrists and forearms, for Test 3, this was performed for the injured wrist only.

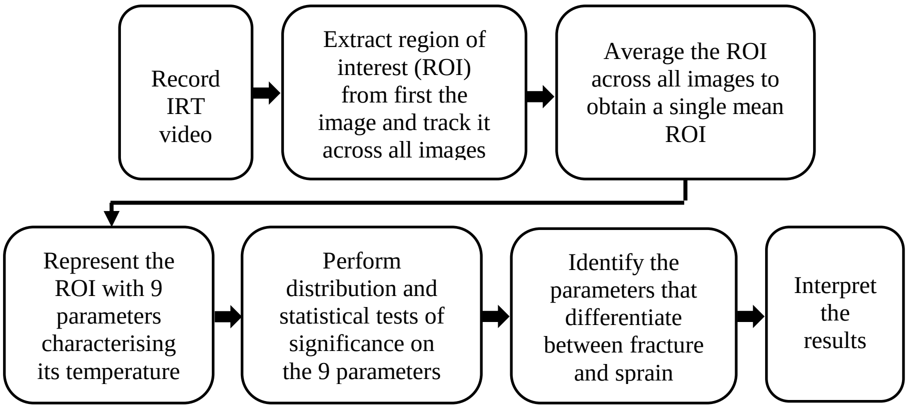

Figure 5 Stages to processing the data

As part of comparing the temperatures of the selected ROIs, T were studied across the two patient groups, i.e. those with fracture and those with sprain. As it was uncertain which statistical parameter could best express T between the two groups, a number of relevant statistical measures were examined. These were: maximum, minimum, mean, standard deviation, median, mode, skewness, kurtosis and interquartile range (IQR) of pixel values for the mean ROI. Representation of mean ROI for a test therefore resulted in a matrix of 9 columns (associated with the 9 parameters) and 40 rows (associated with the 40 patients, of which 19 had a fracture and 21 had a sprain).

The manner which mode was determined varied from the other variables. Given that mode is the most commonly occurring number and as the data had multiple decimal places, its value was not properly represented (as the possibility existed of each number occurred only once). To overcome this, the number of decimal places was reduced to two, prior to identifying the mode. Two decimal places were a compromise between the accuracy of determining the mode and its correct identification.

3.8 Statistical analysis

The analysis to determine whether statistically significant T existed between fractured and sprained wrists for Test 1 comprised of:

- For the 9 parameters across the 40 patients, T between the injured (fractured or sprained) and uninjured wrists was obtained. The Shapiro-Wilk test was then used to establish whether this difference was from a normal distribution. For the Shapiro-Wilk test, the null hypothesis is that the population is from a normal distribution (the hypothesis was rejected when statistical probability (*p*-value) was less than 0.05 for 95% confidence interval, CI).
- For the variables identified to be from a normal distribution, a paired t-test was applied to determine whether the mean T was zero (CI 95%, the null hypothesis was that the mean difference was zero). For variables that could not be confirmed to be from a normal distribution, the Wilcoxon signed-rank test was applied to establish whether the median difference was zero. The null hypothesis was that the difference was not statistically significant.

For Test 2, the procedure was similar to that for test 1, except that the temperature of the arm ROI was subtracted from the wrist's ROI for each arm before the above analysis was performed.

For Test 3, again the procedure was similar to the one in test 1, except that the analysed T was between the injured wrist in flat and 45^{o} elevated positions (the uninjured arm was not used).

4 Results and discussion

4.1 Patient demographics

Table 1 shows the demographics of the 40 included patients. Nineteen patients (47.5%) had a wrist fracture and 21 (52.5%) had a sprain diagnosed (no fracture). The diagnosis was made by clinicians based on the x-ray radiograph. For numerical variables, mean and standard deviations were calculated.

Table 1 Patient demographics. Data are mean (standard deviation). Number of patients in each category is given as N.

Demographic Parameters		Diagnosis Group		Overall
		Fracture **N** = 19 (47.5%)	**Sprain** **N** = 21 (52.5%)	**N** = 40 (100%)
Age (Years)		10.21 (2.82)	10.76 (2.50)	10.50 (2.63)
Weight (kg)		41.21 (18.39)	42.32 (12.17)	41.78 (15.29)
Body temperature (°C)		36.37 (0.47)	36.28 (0.39)	36.32 (0.43)
Time since injury (Hours)		23.70 (35.51)	37.15 (58.71)	30.77 (30.77)
Sex	Female	7 (36.8%)	9 (42.9%)	16 (40.0%)
	Male	12 (63.2%)	12 (57.1%)	24 (60.0%)
Side injured	Right	10 (52.6%)	8 (38.1%)	18 (45.0%)
	Left	9 (47.4%)	13 (61.9%)	22 (55.0%)
Analgesia	None	5 (26.5%)	5 (23.8%)	10 (25.0%)
	Paracetamol	6 (31.6%)	11 (52.4%)	17 (42.5%)
	Ibuprofen	3 (15.8%)	2 (9.5%)	5 (12.5%)
	Paracetamol and Ibuprofen	5 (26.3%)	2 (9.5%)	7 (17.5%)
	Other	0 (0.0%)	1 (4.8%)	1 (2.5%)

4.2 Tests comparing temperatures in fractures and sprains

4.2.1 Test 1 - Temperature comparison of injured and uninjured wrist: flat and elevated

In this test, T between the selected ROI in the injured (fractured or sprained) wrist and the uninjured wrist in the same patient was examined. Table 2 indicates the probability (*p*) -values for the paired t-test or Wilcoxon signed-rank test, depending on the outcome of the Shapiro-Wilk test.

Table 2 Probability values for paired t-test and Wilcoxon signed-rank test of statistical significance to identify the most suitable parameters for discrimination between fracture and sprain.

* indicates *p*-value was determined using the Wilcoxon signed-rank test. Selected statistically significant parameters for fracture but not for sprain are shown in bold-underlined.

Parameter	Fractured Wrist		Sprained Wrist	
	Flat	Elevated	Flat	Elevated
<u>Maximum</u>	0.0020	**<u>0.0014</u>**	0.0363	**<u>0.0519</u>**
Minimum	0.1385	0.1951	0.9705	0.7214
<u>Mean</u>	**<u>0.0075</u>**	**<u>0.0186</u>**	**<u>0.0549</u>**	**<u>0.0544</u>**
Standard deviation	0.2052	0.2954 *	0.2478	0.1455
<u>Median</u>	0.0077	**<u>0.0293</u>**	0.0487	**<u>0.0510</u>**
<u>Mode</u>	**<u>0.0263</u>**	0.0485	**<u>0.1056</u>**	0.0448
Skewness	0.7351	0.4423	0.2259	0.8629
Kurtosis	0.8721 *	0.9679 *	0.2091	0.3219 *
Interquartile Range	0.3862	0.6292 *	0.8407	0.3423

In order to allow discrimination between fractures and sprains, the parameters which showed statistically significant difference in only one of the two injuries were chosen. In situations where the parameter showed a significant difference in both injuries or neither, it was not chosen as it would not differentiate between the two injuries. Based on this, and considering *p*-values <0.05 as statistically significant, the following parameters discriminated the two injuries:

- Maximum with hands in elevated position.
- Mean with hands in both flat and elevated positions.
- Median with hands in elevated position.
- Mode with hand in flat position.

Tables 3 and 4 show the mean and median values for injured (sprained or fractured) and uninjured wrist and their percentage difference.

Table 3 Mean (standard deviation) values of wrist ROI temperature for fracture and sprain in flat and elevated positions

Injury	Temperature (^{o}C) for Wrist in Flat Position			Temperature (^{o}C) for Wrist in Elevated Position		
	Injured Wrist	**Uninjured Wrist**	**Percentage Difference**	**Injured Wrist**	**Uninjured Wrist**	**Percentage Difference**
Fracture	32.512 (1.185)	32.018 (1.400)	1.543%	32.425 (1.400)	31.981	1.388%
Sprain	32.749 (1.069)	32.434 (0.781)	0.971%	32.791 (0.768)	32.505	0.880%

Table 4 Median values of wrist ROI temperature for fracture and sprain in flat and elevated positions.

Injury	Temperature (^{o}C) for Wrist in Flat Position			Temperature (^{o}C) for Wrist in Elevated Position		
	Injured Wrist	**Uninjured Wrist**	**Percentage Difference**	**Injured Wrist**	**Uninjured Wrist**	**Percentage Difference**
Fracture	32.730	32.112	1.925%	32.536	32.094	1.377%
Sprain	32.493	32.175	0.988%	32.521	32.394	0.392%

Tables 3 and 4 indicate that both fractures and sprains caused an increase in wrist temperature. For hands in the flat position, a fracture resulted in an increase in mean and median temperature of 1.543% and 1.925% respectively while a sprain caused an increase in mean and median temperature of 0.971% and 0.988% respectively. When elevated, fractures resulted in an increase in mean and median temperature of 1.388% and 1.377% respectively while sprains resulted in an increase in mean and median temperature of only 0.880% and 0.392% respectively. The temperature increase in fracture was higher than that in sprain in both flat and elevated positions.

4.2.2 Test 2 - Inclusion of forearm as a reference region

This test was included with the aim of compensating for possible baseline temperature difference that may have existed between the two wrists. This was achieved by subtracting the temperature of the reference arm ROI from the ipsilateral wrist ROI. The purpose was to ensure that the temperature difference observed between the two wrists was more representative of (as compared to Test 1) the possible temperature increase caused by the injury.

Table 5 provides the p-values for the paired t-test and Wilcoxon signed-rank tests. For the paired t-test and Wilcoxon signed-rank test the null hypothesis was that the difference between the injured and uninjured wrist ROI, when the arm ROI was subtracted, was not significant.

Table 5 Probability values for paired t-test and Wilcoxon signed-rank tests of statistical significance to identify the most suitable parameters for discrimination.
 * indicates p-value was determined using the Wilcoxon signed-rank test. Selected statistically significant parameters for fracture but not for sprain are shown in bold-underlined.

Parameter	Probability Value (95% CI)			
	Fracture Injury		Sprain Injury	
	Flat Position	Elevated Position	Flat Position	Elevated Position
Maximum	0.7056	0.4056	0.4549*	0.0630*
Minimum	0.8318	0.8405*	0.9824	0.4707
Mean	**0.8870**	0.8980	**0.0417**	0.0680
Standard deviation	0.7271	0.4159	0.6171	0.7082
Median	0.9679*	**0.7475***	0.0701	**0.0386***
Mode	0.1165*	0.6826	0.3597	0.1396*
Skewness	0.7172*	0.3502	0.1919	0.7075
Kurtosis	0.5197*	0.3232*	0.9308*	0.3052
Interquartile Range	0.7984	0.7258	0.6914	0.4837

The following parameters discriminated between the two injuries:

- Mean, with hands in flat position.
- Median, with hands in elevated position.

These two parameters were significant in one injury diagnosis but not the other**.**

4.2.3 Test 3 – Comparison of the temperature of the injured (fractured or sprained) wrist in flat and elevated positions

This test aimed to assess whether the need for comparison with the uninjured arm could be eliminated by comparing the temperature of the injured wrist ROI (sprained or fractured) in flat and elevated positions. Table 6 provides the statistical tests of significance.

Table 6 Probability values for paired t-test and Wilcoxon signed-rank tests of statistical significance to identify the most suitable parameters for discrimination. The significance of the * and values indicated as bold-underline are as in Table 2.

Parameter	Fractured (flat versus elevated)	Sprain (flat versus elevated)
Maximum	0.5779	0.5901
Minimum	0.1842*	0.8350
Mean	**0.0043***	**0.4978**
Standard deviation	0.0994	0.1094
Median	**0.0048**	**0.3652**
Mode	**0.0230***	**0.2589**
Skewness	0.2158	0.1973
Kurtosis	0.8721*	0.8753
Interquartile	0.1825	0.3435

Considering p-values <0.05 as statistically significant, mean, median and mode parameters provided discrimination between fracture and sprain as in one injury type they were significant but not in the other.

4.3 Patient acceptability

In order to establish the acceptability of TI as a screening tool for fracture, patients were asked to give a score 0 (very uncomfortable) to 10 (very comfortable). Figure 6 shows the scores provided for 103 out of 105 patients recruited in the study. Two patients did not complete the questionnaire. The majority of patients were comfortable or very comfortable for the test.

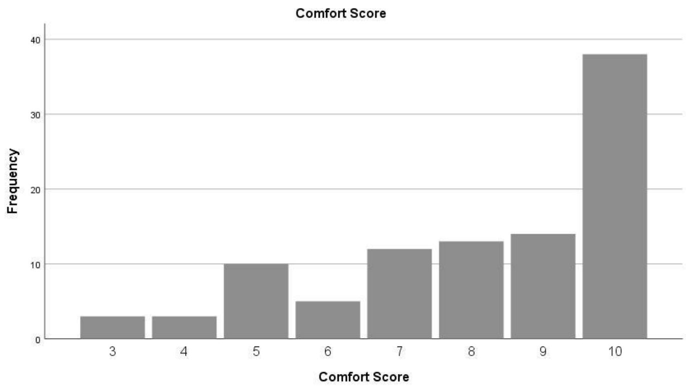

Figure 6 Frequency bar chart representing patient responses to test comfort.

5 Discussion

5.1 Individual Test results

5.1.1 Test 1: Temperature comparison of the injured and uninjured wrists - in flat and elevated positions

A statistically significant temperature difference between the injured (fractured or sprained) and uninjured wrists was observed, with fractures showing a larger *T*. For both fractures and sprains, the underlying physiological processes taking place following injury, including increased perfusion of blood to the site and the acute inflammatory response, could explain the increase in temperature at the site of injury (Oryan, Monazzah and Bigham-Sadegh, 2015, Doblaré, Garcıá and Gómez, 2004, Haluzan et al., 2015, Baoge et al., 2012). Our findings are consistent with earlier studies which found an increase in skin surface temperature following sprains (Oliveira et al., 2016) and fractures (Silva et al., 2012, Sanchis-Sánchez et al., 2015, Fane De Salis, Saatchi and Dimitri, 2018, Ćurković et al., 2015, Haluzan et al., 2015). As a fracture is a more severe injury than a sprain, it is likely that it could cause a greater physiological response and therefore a greater increase in temperature.

The increase in temperature following injury was found to attenuate when the arm was elevated. As gravity acted upon both the fractured and sprained wrists when they were raised by an equal magnitude, it is plausible that the difference in temperature observed when the wrist was elevated was due to the differences in the physiological processes occurring between the two injuries and the manner gravity interacted with these processes. A greater decrease in temperature was observed in fracture when raised from flat to elevated. This might be attributed to there being a larger amount of extracellular fluid and increased blood perfusion to the site in fracture and therefore a greater difference observed when gravity caused this to move from the site.

As an increase in temperature was measured in both sprain and fracture; the finding indicates that thermal imaging may provide a method of identifying injury sites. This could be particularly beneficial in clinical situations when identifying the site of injury in very young children or individuals with communication difficulties. Other studies have reported the use of thermal imaging for this purpose in paediatrics and have found it to be valuable in localising the site of injury (Owen et al., 2017, Silva et al., 2012).

5.1.2 Test 2 Inclusion of the ipsilateral forearm as a reference region to compensate for possible underlying baseline temperature differences between the wrists

The results of this test indicated that for a number of parameters, when the forearm ROI was subtracted from the wrist, sprains showed significant differences from the uninjured wrist whereas fractures did not. One potential explanation for this observation could be that when a fracture occurs, the resulting increase in temperature is more diffuse, thus affecting the temperature of the forearm ROI to a greater extent than more anatomically localised sprains. Therefore it may be plausible that by subtracting the forearm ROI from the wrist ROI in fractures, assuming that both have increased temperature, the observed difference would be diminished. If in the case of a sprain this temperature increase was less diffuse and thus the temperature of the forearm ROI had not increased as much as that in a fracture, then the difference in sprains would become more pronounced.

It is possible that if the reference region had been taken further from the injury site, e.g. in the region of the upper arm, this may have proved effective but this would require further exploration as the current images did not include this region.

5.1.3 Test 3 Comparison of the injured (fractured or sprained) wrist temperature in flat and elevated positions

The purpose of this test was to assess whether a fracture could be differentiated from a sprain using data from only the injured wrist. The test indicated that there were statistically significant differences distinguishing fractures from sprains for a number of parameters. The temperature of the fractured wrist was significantly different between flat and elevated positions whereas in sprain it was not. In terms of the suitability and clinical applicability of this approach, it may have some advantages over the approach described in Test 1. One of the key benefits to this approach is that it does not require a comparison to be made with the uninjured wrist. This would mean that any possible baseline temperature variability between the two wrists would not affect the results. Additionally, this approach would be suitable in cases where the other wrist is not suitable or available for comparison. For example, this approach might be utilised in cases where injury has been sustained to both wrists, or where there is pathology to the uninjured wrist, such as arthritis or burns, which would affect the skin surface temperature of the wrist and make comparison inappropriate. In future we will investigate whether this approach can differentiate between fracture and sprain in cases excluded from this study (i.e. those with applied ice or covered sleeves).

A drawback to this approach would be instances in which the child is unable to move their wrist from the flat to elevated position due to pain, although in our experience this scenario is rare.

Although there have been a number of studies investigating blood flow in fracture healing (Kanczler and Oreffo, 2008, Tomlinson and Silva, 2013) and the effect of gravity of blood pressure (Martin-Du Pan, Benoit and Girardier, 2004), there are not any, to our knowledge, which examines specifically how gravity effects blood perfusion and extracellular fluid distribution at the site of fracture and sprain.

5.2 Quantification of the impact of adapting thermal imaging for fracture screening protocol

As highlighted in earlier sections, adaptation of thermal imaging as part of the fracture screening protocol may reduce the number of unnecessary x-rays. This in turn would reduce exposure to x-ray radiation. The amount of radiation delivered by medical imaging is described in terms of ‘effective dose’. This radiation is measured in millisieverts (mSv) and is the product of the ‘absorbed dose’ and a ‘weighing factor’ which takes into account the location irradiated, radiation type and regimen delivered (Davies, Wathern and Gleeson, 2011). This effective dose indicates the radiation effect of a specific imaging procedure in terms of estimated equivalent whole body radiation dose and allows the exposure associated with different imaging modalities to be compared (Davies, Wathern and Gleeson, 2011). In order to contextualise the dose of different procedures, the effective dose is often described as a proportion of the background radiation each person receives over the course of a year. Background radiation is emitted from environmental and cosmic sources and an average individual will be exposed to an effective dose of around 2.4 mSv per annum (Davies, Wathern and Gleeson, 2011). The mean estimated radiation dose of a radiograph of the wrist in children is around 0.001 mSv, which is less than a day’s worth of background radiation (Lin, 2011). To compare this to a more significant investigation, a radiograph of the abdomen would have radiation dose of 1.2 mSv, around the equivalent of 5 months of background radiation (Lin 2010). Although the radiation dose delivered by a wrist x-ray is comparably small, any amount of radiation could lead to potentially carcinogenic DNA damage and exposure should be reduced wherever possible.

We did not the data to account for the global financial impact of x-rays taken for fractures. However, we have tried to illustrate this point with the data available to us from the hospital where this study was carried out. An unpublished Emergency Department (ED) audit attributed a cost of £54 to a single x-ray radiograph. Between 2016-2018, an average of 1479 wrist x-rays were performed in the ED, predominantly for the diagnosis of fracture (Table 7). If we consider the finding of Slaar et al (2012), that estimated 49% of wrist x-rays reveal no underlying fracture, we can estimate that 725 of these x-rays could have resulted in negative findings. This would give an estimated cost of £39,150 annually attributed to negative radiological investigations for a single medium-sized hospital ED.

Table 7 Wrist x-rays requested at study ED and estimated cost

Year	Number of wrist x-rays performed	Estimated number of negative findings (49%)	Estimated cost of negative finding
2016	1433	702	£37,908
2017	1488	729	£39,366
2018	1517	743	£40,122
Mean	1479	725	£39,150
Total 2016-2018	4438	2174	£117,396

This is only the cost of negative radiological wrist investigations, considering the investigative radiological examinations of other bones performed, the overall cost will be much higher. The findings also reveal the number of wrist x-rays performed has increased each year, supporting findings that the incidence of wrist fracture is increasing (Nellans, Kowalski and Chung, 2012).

The deployment of thermal imaging in a clinical setting for fracture screening can incur costs. The thermal camera can cost typically around £15,000 (depending on the model). It has a small running cost, primarily yearly calibration. Its application would add to the screening time by a few minutes. It may also risk an over-reliance on its findings as a screening tool, resulting in missing some fractures requiring follow on x-ray diagnosis. However, through suitable training this could be mitigated against.

5.3 Areas of further work

There are a number of potential areas for exploration based on this study. Some of these are outlined below.

Stratifying by time: Time since injury is a factor which effects skin surface temperature following a fracture due to the variations in the underlying healing processes taking place across time (Haluzan et al., 2015, Ćurković et al., 2015). It may have been advantageous to stratify patients by time since injury in the analysis; however, as only 40 patients were included in this study, this stratification would have resulted in small subgroups which could have adversely affected the accuracy of statistical testing. In a study with a significantly larger number of patients, this investigation could be considered. Another closely related area of further work would be the determination of at what point in time thermal imaging may no longer able to distinguish between fracture and sprain post-injury.

Analgesia: Nonsteroidal Anti-Inflammatory Drugs (NSAIDs) are known to have an impact on inflammation and body temperature. The anti-inflammatory, antipyretic effect of NSAIDs is mainly achieved through the inhibition of cyclooxygenase isoenzymes-2 (COX-2) enzyme, which is induced in inflammatory cells (Wongrakpanich et al., 2018). NSAIDs have been shown to have an effect on internal body temperature, primarily through their effects on prostaglandin synthesis and inhibition (Murphy, Myers and Badia, 1995). Although these effects are known, the specific effects of NSAIDs and other drugs on skin surface temperature are yet to be investigated. This would be a useful area of further research to determine the effect this might have on the implementation of thermal imaging in patients who have taken medications.

Effect of ice: Patients who had ice applied to the injury site were excluded from analysis. In future work, our plan is to analyse the temperature profile of these patients to determine how the application of ice may affect the injury discrimination accuracy.

Scaphoid fracture: Fractures of the scaphoid can be challenging to detect on x-ray as they are often not easily visible on initial films, which have a reported sensitivity of around 70% (Rhemrev et al., 2011). Conventional management is immobilisation using a splint and repeat radiographs after 10-14 days. However, even at this point fractures may continue to be missed as the follow-up radiographs have poor sensitivity (Low and Raby, 2005). Studies have suggested that MRI might be suitable to replace x-ray as the gold-standard diagnostic tool for occult scaphoid fractures, however this technology is expensive and no significant savings with the implementation of this technology over traditional management have been found (McCullough, Smith and Cooper, 2011). In a study by Owen et al. (2017), thermal imaging was found capable of detecting occult cases of toddler's fracture which has previously been missed on x-ray. Although no patients with scaphoid fracture were recruited to this study, there is the possibility that thermal imaging may be able to detect this occult fracture, providing a low-cost method of identification, and this could be a valuable area of further research.

Other bones: It would be valuable to conduct further research to determine which areas of the body thermal imaging is capable of distinguishing between fractures and sprains, or in multiple trauma to rapidly identify significant areas of injury.

Larger Sample Size: Power calculations to determine appropriate sample size were not performed in this study as, due to the nature of it being an exploratory study and insufficient information being available on which to base the related power calculations. It therefore cannot be guaranteed that the rejection of the null hypothesis in this study is not a type I error. However, the sample size of this exploratory study was sufficient to show proof of concept and indicated that further research into the use of thermal imaging for this purpose would be beneficial. Further research into this application of thermal imaging with an adequately powered study would be now possible to validate the conclusions drawn from this pilot study.

Duration of imaging and remaining still: The thermal imaging recordings required the child to remain still for two sets of 30-second recordings. This however proved challenging for a few children, particularly the younger ones, who became bored. Exploration of the minimum recording time that can show significant results would be valuable.

Severity of injury: Another factor which may affect the ability of thermal imaging to distinguish between fracture and sprain is the severity of the injury. Within this study, the severity of the sprain or fracture attained was not taken into account, for example a mild buckle fracture would be grouped with a complete fracture, which is a significantly more severe injury. It may be that the ability of thermal imaging to distinguish between fracture and sprain is limited in cases of particularly mild fracture or severe sprain in which the temperature differences may more closely resemble one another. If it were to be the case that thermal imaging was likely to miss less severe fractures which may still require treatment, then thermal imaging would have reduced applicability as a screening tool for fractures.

Other bones of the wrist: Of the patients recruited to this study who were diagnosed with wrist facture on x-ray, all were found to have sustained injury to the distal radius or ulna as opposed to the carpal bones. This is in keeping with data showing that fractures of the carpal bones are rare in children (Arora et al., 2014). From this study, it is therefore not possible to comment on the efficacy of thermal imaging in detecting fractures of the carpal bones although further investigation into the ability of thermal imaging to detect these fractures could be beneficial.

Other underlying pathology: Studies have demonstrated that a number of bone and joint pathologies, for example arthritis and osteomyelitis, will affect the skin surface temperature measured at the site (Zhao et al., 2018, Lasanen et al., 2015). A limitation of this study is that the presence of underlying pathologies was not explored and there is therefore the potential that the patients recruited to the study may have had other undiagnosed pathologies, that may have had an effect on the results attained and may have caused an increase of temperature not attributed to the presence of sprain or fracture. Although the presence of underlying undiagnosed pathology is unlikely, this may need to be investigated in further research.

6 Conclusion

This study indicated that for the arms in both flat and 45^{o} elevated positions, both sprain and fracture showed a mean temperature increase at the site of the injury as compared to the uninjured wrist region of interest (ROI) of the same patient. This increase was significant for fractures but not in sprains, indicating that it may allow differentiation between the two diagnoses.

Sprained wrists were found to have significant temperature differences between the injury ROI and the ipsilateral reference ROI. This finding was not reproduced in fractured wrists, and may therefore also be useful in excluding fractures.

Finally, the difference in temperature of the fractured wrist when the forearm was raised from a flat to an elevated position was significant whereas in sprains this difference was not significant.

Considering the results and findings of this study it can be concluded that significant differences exist between fractures and sprains when measured using infrared thermal imaging, These differences may be used to assist in their differentiation as a screening or diagnostic adjunct.

7 Acknowledgements

We would like to thank the children and their carers who very kindly participated in the study as without their support this work would have been impossible. We also would like to thank the clinicians at the Sheffield Children's Hospital, United Kingdom, for welcoming research in the clinical environment, helping with recruitment and screening. This study was part funded by a grant from The Children's Hospital Charity to SR.

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