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Infrared thermal imaging for bone fracture identification and monitoring of fracture healing: A review of the latest developments

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Abstract

Infrared thermography (IRT) is a non-destructive imaging technology which detects thermal energy emitted from objects and converts it into numeric and visual data. IRT has been receiving increasing interest by clinicians as a non-invasive and safe tool for medical diagnosis and monitoring. Studies have reported the potential of IRT for physiological measurements, medical diagnosis and monitoring. In this paper, developments in the applications of IRT for bone fracture identification and the monitoring of fracture healing are reviewed. A significant proportion of x-rays taken to diagnose bone fracture are negative, i.e. reveal that there is no underlying fracture. IRT may have potential as a screening tool to filter out these negative cases where the injury has not resulted in fracture. Exclusion of cases without an underlying fracture would reduce the cost and exposure to harmful radiation associated with unnecessary x-ray imaging. In infants and young children, who may not be able to accurately report the site of injury, IRT may assist in locating possible injury sites, thus facilitating more timely treatment. This feature could also be valuable in child abuse cases with possible bone fracture. Some fractures, such as toddlers fracture, may not be visible on an initial x-ray examination and repeat x-ray imaging is required around two weeks later to confirm diagnosis. IRT may be able to assist clinicians in the initial assessment of such fractures, enabling a more timely diagnosis.

Key words: Infrared thermal imaging, bone fracture identification, fracture healing monitoring, non-destructive testing.

1. Introduction

Objects at a temperature above absolute zero (-273ºC or 0 degrees Kelvin) emit infrared (IR) radiation. IR radiation increases with temperature and consists of electromagnetic waves, produced by protons traveling at the speed of light in a wavelike pattern. Modern IRT devices are able to detect IR radiation and convert these measurements into thermal images, producing visual 'temperature maps'. A thermal image is formed of a matrix of Picture

Elements (pixels) in which each pixel conveys temperature information of a spatial location; the colours displayed are a reflection of the assignment of different colours to each IR energy level [(1-4)].

In humans, body temperatures within the range of 36.3-37.5 ºC can be considered normal; temperatures outside of this range can be indicative of illness [(5)]. The temperature of the skin is more variable than internal body temperature. It is influenced by the perfusion of blood to the underlying tissue and skin, which is in turn influenced by both thermal regulation, physiological and pathological processes [(6)]. The temperature is also influenced by other factors, including: environmental conditions, physical workload, metabolic state, drug effects, circadian rhythms and the person's psychological state [(7)]. Under environmental conditions of between 18-25 ºC, thermal radiation from the skin is the main method by which regulation of body temperature is achieved [(7)]. Blood is the medium through which the heat generated from metabolic processes, is transferred around the body and maintains a homoeothermic balance. When the body becomes too warm, blood flow to the skin will increase, allowing more heat to dissipate into the environment; conversely, when the body becomes too cold blood flow to the skin decreases to conserve heat [(8)]. As increased blood perfusion increases skin surface temperature, various underling physiological processes and pathologies involving inflammation and alterations to perfusion will therefore also cause a change in skin surface temperature; changes which may be detected by infrared thermal imaging (IRT).

The first medical application of thermography was in 1959, when 'The Pyroscan' was first used to image the skin temperature changes over arthritic joints [(9)]. This device however was unable to quantify these temperature changes. The addition of computer processing systems in the 1970s allowed quantified temperature measurements to be obtained from selected 'Regions of Interest' (ROIs) from the images [(10)]. Since this preliminary work, numerous studies have aimed to evaluate the use of IRT in measuring the skin surface temperature changes associated with various pathologies and how this technology may be implemented in the medical field. Significant technological advancements in recent years have produced IRT devices which are more cost effective, portable and capable of attaining more accurate results [(5)]. These improvements have led to growing diversification and interest in the potential medical applications of IRT [(1-4)], including for bone fracture diagnosis and fracture healing monitoring [(11-17)].

At present plain radiographs or 'x-rays' are the gold-standard investigative imaging technique for fractures. They are usually effective in identifying fractures when utilised effectively. One of the main disadvantages of x-rays is the associated exposure to ionising radiation. The ionising radiation produced by x-rays is capable of causing damage to DNA through the production of hydroxyl radicles; these radicles can interact with DNA causing strand breaks or damage to the bases [(18)]. The majority of this damage will be repaired but faults in the repair process can cause chromosomal translocations, gene fusions and point mutations in the DNA which can lead to radiation induced carcinogenesis [(19)]. Advantages of IRT include: it is a non-destructive and passive method of imaging, it does not emit harmful ionizing radiation, and it is more cost effective to perform than other scanning modalities [(20)].

When a fracture occurs, the physiological changes occurring beneath the skin lead to temperature changes of the surface at the fracture site. Initially, there is disruption to the vascular supply and an acute inflammatory response as inflammatory cytokines accumulate at the injury site, these changes increase the temperature of the surrounding tissues [(16)]. Using

IRT these temperature changes are measured and interpreted to perform physiological measurements, medical diagnosis and monitoring.

In the following sections, the anatomy of bone is briefly explained, fracture mechanisms and healing briefly outlined, the methodology used to carry out the review is explained and the results of the review are provided.

2. Bone anatomy and fracture healing

The adult human skeleton has 213 bones (excluding the sesamoid bones). They can be categorised as [(21)]:

- Long bones: include the clavicles, humeri, radii, ulnae, metacarpals, femurs, tibiae, fibulae, metatarsals, and phalanges.
- Short bones: include the carpal and tarsal bones, patellae, and sesamoid bones.
- Flat bones: include the skull, mandible, scapulae, sternum, and ribs.
- Irregular bones: include the vertebrae, sacrum, coccyx, and hyoid bone.

The long bones consist of a diaphysis (primarily of dense cortical bone), metaphyses below the growth plates and epiphyses above the growth plates. The metaphysis and epiphysis are composed of trabecular meshwork bone surrounded by a relatively thin shell of dense cortical bone [(21)].

The healing process that occurs following a fracture is divided into three phases based on the underlying physiological processes taking place at that time; these being the inflammatory, reparative and remodelling phases [(16)]. The inflammatory phase occurs immediately following a fracture. This is characterised by the formation of a haematoma at the site as a result of bleeding of the ruptured bone and periosteal blood vessels [(22)]. During the reparative phase there is organisation of the fracture haematoma and the granulation tissue is replaced to form a collagenous fracture callus at the site. This cartilage is gradually transformed into immature (woven) bone by the process of endochondral ossification and to a lesser extent, intramembranous ossification [(22)]. The remodelling phase is the stage in which osteoclasts resorb the woven bone of the ossified callus and osteoblasts replace the immature bone with lamellar bone. This phase bears similarities to the modelling and remodelling seen in normal bone and restores the mechanical strength and stability of the bone at the site of the fracture [(22)].

3. Methodology

The literature review was performed using the Google search engine. The articles were found with the specific combination of keywords: Thermal Imaging AND Bone Fracture, Thermal Imaging AND Bone Fracture Healing. This literature survey was finalized on 1st of May 2021.

4. Results

In this section, a review of the studies reporting findings related IRT based fracture diagnosis and fracture healing monitoring is provided.

4.1. IRT assisted bone fracture diagnosis

The potential of IRT for locating the site of and ruling out fractures in a paediatric population has been studied. In one study, both x-ray imaging and IRT were undertaken in 51 children for fracture diagnosis [(11)]. It found that IRT could accurately match the area of pain in 73% of patients and matched 64% of the fracture sites. In another study, 145 children who had sustained traumatic injury and were undergoing diagnostic x-ray were recruited (12 were later excluded) and IRT was performed. It was reported that IRT has a sensitivity of 91% in detecting fracture and it was concluded that IRT could be effective in ruling out paediatric fractures [(17)].

IRT has been studied as a method to detect thoracic vertebral fractures in osteogenesis imperfecta (OI) [(14)]. OI, also known as brittle bone disease, is caused by a mutation in the type I collagen gene resulting in structurally weakened bones which are more susceptible to fracture, deformity and growth deficiency [(23)]. Due to recurrent fractures, children with OI are subject to frequent x-rays and bone densitometry (DXA) scans and to the harmful ionising radiation associated with these imaging technologies. The study recruited 11 patients aged 5-18 years with a diagnosis of OI and vertebral fractures. The study showed that there was a statistically significant temperature percentage change (TPC) when the skin overlying fractured thoracic vertebrae was compared to their adjacent reference regions of skin, but that this TPC was not significant when the skin overlying non-fractured thoracic vertebrae was compared likewise. These findings demonstrated the potential of IRT for the detection or monitoring of thoracic vertebrae fractures in paediatric patients with OI [(14)].

IRT was found to be valuable for assisting with diagnosing the cause of limp [(15)]. The causes of limp include traumatic injury, infection and malignancy. The study included 30 children - amongst whom were two cases with toddler's fractures. Toddler’s fracture is a none-displaced spiral fracture of the tibia in children aged below 5 years. Toddler's fracture may not be visible on the initial x-ray images and a repeat x-ray is required after 10-14 days to confirm the diagnosis [(24)]. IRT performed at the two patient’s initial presentations to hospital pointed to the fracture site by demonstrating a ‘hotspot’ overlying the fracture, before it became visible on x-ray. This may indicate the potential of IRT to detect fractures prior to their becoming visible on x-ray, however, a larger sample size would be required to confirm this.

Wrist injuries are common in the paediatric population with fractures of the distal radius accounting for 25% of all fractures in this population [(25)]. Diagnostic x-ray is usually performed when a fracture is suspected, in as many as 91% of children presenting with a wrist injury [(26)]. However around 50% of these x-rays fail to demonstrate an underlying fracture [(27)]. One study showed that there was a significant temperature difference between the region of interest (ROI) associated with the fracture site of the injured wrist and the same region on the uninjured wrist [(13)]. The temperature difference between these regions in the case of sprain was not statistically significant. The researchers also observed that there was a significant temperature change at the site of wrist fracture when the forearm was raised to 45 degrees elevation, whilst this temperature change in sprains was not significant; this alternative comparison eliminated the need to have the uninjured arm available for comparison. The findings of this study indicated the potential of IRT as a screening tool for paediatric wrist fractures.

4.2 IRT based fracture healing monitoring

Monitoring bone fracture healing could allow assurance that fracture union is progressing adequately. Fracture non-union can cause patient morbidity. X-ray radiographs have limitations when used for this purpose as the bridging callus of long bone fractures can take at least 3 months to occur [28]. Computer tomographic (CT) imaging can also be used to assess bridging callus in the late stages of bone fracture healing. Dynamic contrast enhanced magnetic resonance imaging (CE-MRI) may be valuable in evaluation of the infected bone fracture non-union [28].

In one study, twenty-five adult patients were recruited and the temperatures of the distal radius of the fractured and healthy forearms were measured using IRT [16]. An increase in skin surface temperature of the fractured wrist was observed, in comparison to the uninjured wrist during fracture healing. Comparing the injured and uninjured wrists, they found the temperature of the fractured wrist was higher between 1 to 11 weeks post-injury. This increase peaked at 3 weeks post-injury.

Skin surface temperature changes during fracture healing within a paediatric population were monitored using IRT in 19 patients [29]. The patients, aged 4 to 14 years, had sustained forearm fractures. IRT of the fractured and uninjured wrists at 7, 14 and 21 days post-injury were conducted. It was observed that the temperature difference between the fractured and uninjured forearm was greatest 7 days post-injury. This decreased at 14 days post-injury and was minimal at 21 days post-injury. Given the findings in adults [29] and paediatrics [16], the peak increase in temperature following injury in children was earlier as compared to adults. This difference may be because the process of microvascular invasion and fracture healing occurs more quickly in children than that in adults due to increased vascularity.

5. Discussion

X-ray radiography provides good resolution images of bone, allowing bony injuries to be visualised and treatment or surgical intervention to be determined and guided. X-ray is widely available, non-invasive and painless. It has a lower cost in comparison to magnetic resonance imaging (MRI). Furthermore it is not affected by typical variations in environment and is also capable of capturing images when the limb is covered, for example with a cast. The main disadvantage of x-ray is exposure to harmful ionizing radiation [30], it therefore follows that an imaging technology reducing the number of unnecessary x-rays undertaken would be beneficial.

Multiple strengths of IRT were stated in the literature, including: cost effectiveness, faster scanning (compared other imaging modalities), real-time imaging and its non-contact nature [20,31]. The non-contact nature of this imaging technology has been demonstrated to be of particular benefit when utilized in the paediatric population, who are typically poorly tolerant of devices which come into contact with the body [3]. In young children and infants, who may be unable to accurately report the site of injury, IRT could assist in localising the site of fracture thus allowing more timely treatment [11]. Initial findings have indicated that IRT may be able to detect some fracture types earlier than they can be detected on x-ray i.e. toddler's fracture, which may allow the making of a more timely diagnosis and guide the most appropriate treatment [15]. Unlike x-ray radiographs, which are static images providing the status of the injury site at a moment in time, IRT can be dynamic, producing video recordings which may allow closer examination of blood perfusion at the injury site over time.

However there are also some limitations to the use of IRT. As the thermal image records only the temperature of the surface of the skin, it is not able to reveal details about, or provide visualisation of the underlying pathology [32]. For example, if it is used to detect fracture, it cannot provide visualisation of bone itself that provides diagnostic reassurance. Its ability to accurately record skin surface temperature is impaired if environmental conditions are not within set temperature range or are not consistent [33]. Given the nature of the technology, it is also not suitable if the area is covered, for example, if the area was covered by a cast or clothes then thermal imaging would not be possible. Accuracy of recordings can also be affected if there is a very light covering of the skin, such as an ointment or wound secretions [7].

6. Conclusions

Infrared thermal imaging (IRT) has been reported in several studies to have potential as a screening tool for bone fracture. This can reduce the number of unnecessary x-rays performed i.e. those indicating there is no underlying fracture and reduce the cost and exposure to harmful ionizing radiation associated with these x-rays. IRT also could be valuable for monitoring fracture healing. IRT can be performed quickly, is cost effective, and can be repeated as many times as needed without exposing patients to harmful radiation, which is particularly beneficial in patients requiring frequent fracture screening, i.e. in osteogenesis imperfect. However, further developments are required to adapt IRT as a routine diagnostic tool in clinical environments.

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References

1. C Barson, R Saatchi, P Godbole, and S Ramlakhan, 'Infrared thermal imaging to detect inflammatory intra-abdominal pathology in infants', WSEAS Transactions on Biology and Biomedicine, Vol 17, pp 82-98, July 2020.
2. H Nwaizu, R Saatchi, D P Hawley and O Ward, 'Thermal and visual imaging to assist with juvenile idiopathic arthritis examination of the knees', Technologies, Vol 8, No 30, pp 1-19, May 2020.
3. H Elphick, A H Alkali, R K Kingshott, D Burke and R Saatchi, 'Exploratory study to evaluate respiratory rate using a thermal imaging camera'. Respiration: International Journal of Thoracic Medicine, Vol 97, No 3, pp 205-212, January 2019.
4. A H Alkali, R Saatchi, H Elphick and D Burke, 'Thermal image processing for real-time noncontact respiration rate monitoring', IET Circuits, Devices and Systems, Vol 11, No 2, pp 142-148, March 2017.
5. B B Lahiri, S Bagavathiappan, T Jayakumar and J Philip, ‘Medical applications of infrared thermography: A review’, Vol 55, No 4, pp 221-235, July 2012.
6. I Campbell, ‘Body temperature and its regulation’, Anaesthesia and Intensive Care Medicine, Vol 12, No 6, pp 240-244, June 2011.

7. A K Saxena and G H Willital, 'Infrared thermography: Experience from a decade of pediatric imaging' European Journal of Pediatrics, Vol 167, pp 757-764, July 2008.
8. C L Lim, C Byrne and J K Lee, 'Human thermoregulation and measurement of body temperature in exercise and clinical settings', Vol 37, No 4, pp 347-353, April 2008
9. E F J Ring, 'The historical development of thermal imaging in medicine', Rheumatology, Vol 43, No 6, pp 800-802, June 2004
10. E F J Ring, 'The historical development of thermometry and thermal imaging in medicine', Journal of Medical Engineering & Technology, Vol 30, No 4, pp 192-198, July-August 2006.
11. C T Silva, N Naveed, S Bokhari, K E Baker, L H Staib, S M Ibrahim, K Muchantef and T R Goodman, 'Early assessment of the efficacy of digital infrared thermal imaging in pediatric extremity trauma' Emergency Radiology, Vol 19, pp 203-209, February 2012.
12. R Vardasca, C Magalhaes, P Silva, P Abreu, J Mendes and M T Restivo, 'Biomedical musculoskeletal applications of infrared thermal imaging on arm and forearm: a systematic review', Journal of Thermal Biology, Vol 82, pp 164-177, May 2019.
13. C Reed, R Saatchi, D Burke and S Ramlakhan, 'Infrared thermal imaging as a screening tool for paediatric wrist fractures' Medical and Biological Engineering and Computing, Vol 58, pp 1549-1563, May 2020.
14. A Fane De Salis, R Saatchi and P Dimitri, 'Evaluation of high resolution thermal imaging to determine the effect of vertebral fractures on associated skin surface temperature in children with osteogenesis imperfecta', Medical and Biological Engineering and Computing, Vol 56, pp 1633-1643, February 2018.
15. R Owen, S Ramlakhan, R Saatchi and D Burke, 'Development of a high-resolution infrared thermographic imaging method as a diagnostic tool for acute undifferentiated limp in young children' Medical and Biological Engineering and Computing, Vol 56, pp 1115-1125, November 2017.
16. D Haluzan, S Davila, A Antabak, L Dobric, J Stipic, G Augustin, T Ehrenfreund and I Prlic, 'Thermal changes during healing of distal radius fractures – Preliminary findings' Injury, Vol 46, No 6, pp 103-106, November 2015.
17. E Sanchis-Sánchez, R Salvador-Palmer, P Codoñer-Franch, J Martín, C Vergara-Hernández, J Blasco, E Ballester, E Sanchis, R González-Peña and R Cibrián, 'Infrared thermography is useful for ruling out fractures in paediatric emergencies' European Journal of Pediatrics, Vol 174, pp 493-499, April 2015.
18. E C Lin, 'Radiation risk from medical imaging', Vol 85, No 12, pp 1142-1146, December 2010
19. D J Brenner and E J Hall, 'Computed tomography – an increasing source of radiation exposure' The New England Journal of Medicine, Vol 357, No 22, pp 2277-2284, November 2007.
20. C Hildebrandt, C Raschner and K Ammer, 'An overview of recent application of medical infrared thermography in sports medicine in Austria, Sensors, Vol 10, pp 4700-4715, 2010.
21. B Clarke, 'Normal bone anatomy and physiology', Clinical Journal of the American Society of Nephrology, Vol 3, No 3, pp 131–139 November 2008.
22. A Oryan, S Monazzah, and A Bigham-Sadegh, 'Bone injury and fracture healing biology', Biomedical and Environmental Sciences, Vol 28, No 1, pp. 57-71, January 2015.
23. N Bishop, 'Characterising and treating osteogenesis imperfecta' Early Human Development, Vol 86, No 11, pp 743-746, November 2010.
24. N Alqarni and R D Goldman, 'Management of toddler's fracture' Canadian family physician Medecin de famillle canadien, Vol 64, No 10, pp 740-741, October 2018.

25. K W Nellans, E Kowalski and K C Chung, ‘The Epidemiology of Distal Radius Fractures’ Hand Clinics, Vol 28, No 2, pp 113-125, May 2012.
26. C L van den Brand, R H van Leerdam, J H M E Q van Ufford, S J Rhemrev, ‘Is there a need for a clinical decision rule in blunt wrist trauma?’, Injury, Vol 44, No 11, pp 1615-1619, November 2013.
27. A Slaar, A Bentohami, J Kessels, T S Bijlsma, B A van Dijkman, M Maas, J C H Wilde, J C Goslings and N W L Schep, ‘The role of plain radiography in paediatric wrist trauma’ Insights Imaging, Vol 3, No 5, pp 513-517, October 2012.
28. J A Nicholson, L Z Yapp, J F Keating and A H R W Simpson, 'Monitoring of fracture healing. Update on current and future imaging modalities to predict union', Injury, DOI: https://doi.org/10.1016/j.injury.2020.08.016, 2020, Last accessed 08/05/2021.
29. S Ćurković, A Antabak, D Halužan, T Luetić, I Prlić and J Šiško, 'Medical thermography (digital infrared thermal imaging - DITI) in paediatric forearm fractures - A pilot study', Injury, Vol 46, No 6, pp S36-S39, November 2015
30. H Kasban, M A M El-Bendary and D H Salama, 'A comparative study of medical imaging techniques', International Journal of Information Science and Intelligent System, Vol 4, No 2, pp. 37-58, March 2015.
31. J Hardwicke, R Thomson, A Bamford and N Moiemen 'A pilot evaluation study of high resolution digital thermal imaging in the assessment of burn depth', Burns, Vol 39, No 1, pp. 76-81, February 2013.
32. E F J Ring and K Ammer, 'Infrared thermal imaging in medicine', Physiological Measurement, Vol 33, No 3, pp 33-46, March 2012.
33. K Ammer, F J Ring, 'Medical infrared imaging: principles and practice', CRC Press, Taylor and Francis Group. Editors: Mary Diakides, Joseph D Bronzino, Donald R Perterson, 2012.