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Biomedical musculoskeletal applications of infrared thermal imaging on arm and forearm: A systematic review

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ABSTRACT

Infrared thermal imaging (IRT) has been a target of research for biomedical musculoskeletal applications, due to the possible association of the physiological data that it provides, through skin temperature measurement, with pathological states. The aim of this systematic review is to acquaint the outcomes of the biomedical application of IRT in arm and forearm evaluation and its future perspectives of research. During the literature review, 926 articles were identified using the search engines PubMed and Scopus, and 10 articles were retrieved from other sources. After screening the abstracts and applying the eligibility criteria on those which were fully accessible, 33 articles were included in the review. It can be observed that IRT has the potential to provide physiological information on the arm and forearm, showing potential to serve as an aid in various pathologies and health situations. Future studies and challenges are identified and proposed, facilitating the improvement and acceptance of the application of IRT in the assessment of arm and forearm' health status.

1. Introduction

Upper limb disorders and conditions may be caused by physical exertion, prolonged exposure to risk factors or senesce. These pathologies can compromise a person's motor capability, life independence and overall quality of life (Piper et al., 2015), justifying the interest in the development of upper limbs assessing tools and methodologies. One promising technology is infrared thermal imaging (IRT).

The human body has the ability to keep its normal function through the maintenance of core temperature (Nola and Kolanc, 2015). The skin, the largest organ of the human body, plays an important and essential role in this process, being most of the internal generated heat spread to the surrounding environment by radiation (Nola and Kolanc, 2015). This can be recorded with IRT using thermal cameras.

IRT imaging provides information through the mapping of skin temperature. The acquired thermal patterns reflect underlying physiology that is affected by peripheral blood flow regulated by the autonomous nervous system (Nola and Kolanc, 2015; Ring and Ammer, 2012). Over six decades of application in the biomedical field, this imaging modality has proved its value in the documentation of pathological conditions at the musculoskeletal, vascular, neurological and tegumentar systems (Ring and Ammer, 2012; Jones and Plassmann, 2002). The technique can be used statically, a passive recording, or dynamically, through the use of a stimuli, creating a temperature imbalance that can be monitored until thermal equilibrium is reached to provide deeper physiological information (Anbar, 2013). These stimuli can be thermal (cold or hot), mechanical (exercise or vibration exposure) or chemical (drugs) (Ammer and Ring, 2013).

Minimal requirements for medical applications of thermal cameras have been specified (Howell and Smith, 2019) and international standards have been published (ISO TC121/SC3-IEC SC62D, 2017; ISO TC121/SC3-IEC SC62D, 2017). Simple tests for assessing the recording equipment for minimal quality assurance warranty were proposed as good IRT screening practice (Ring et al., 2007). Along with this, international guidelines concerning image acquisition were produced, being focused on patients/participants' preparation before and during examination, room conditions, equipment preparation and manner of image recording (Ring and Ammer, 2000; Ammer, 2008). It is very important to follow these recommendations to standardize the process and reduce the influence of variables (Fernandez-Cuevas et al., 2015) that can affect the examination, emphasizing the comparison among centers and promoting knowledge exchange.

When applied to upper limbs surface temperature monitoring, this technique provides physiological data that can be linked to

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Table 1
Revised articles found in the literature survey.

Reference	Title	Aim	Methodology	Major Results	Conclusions	Open Challenges
(Vardasca et al., 2018)	Skin Temperature Bilateral Differences at Upper Limbs and Joints in Healthy Subjects	To investigate healthy individuals, providing reference values, which would be a future reference for further screening in aiding diagnosis or benchmarking physiotherapy and rehabilitation treatments in an objective manner.	40 Healthy participants were screened with infrared images (using the thermal camera FLIR A325sc) of regions of interest such as arm, forearm, hand, shoulder, elbow and wrist, in both anterior and posterior views. These images were used to determine the mean temperature distribution and bilateral difference values.	The highest bilateral difference was observed on the anterior surface of the forearm and the smallest was found at the shoulder ROIs.	The bench-mark of bilateral difference on temperature distribution has significant value for assessments of vascular, neurological or musculoskeletal conditions that manifest themselves unilateral, affecting thermal skin patterns.	–
Gabrhel et al. (2017)	The Role of Infrared Thermal Imaging and Sonography in the Assessment of with a Painful Elbow	To investigate the value of infrared thermography (IRT) and sonography for the differential diagnosis of elbow pain	Retrospective chart review of 116 patients with painful elbow was conducted and underwent a complete clinical, musculoskeletal, thermographic analysis (including the arm and forearm region and using the Ti32 Fluke thermal imager) and sonographic examination. The thermographic analysis was performed using the standard positions of the Glamorgan protocol and additional anterior and posterior projections with full elbow extension.	Thermal imaging detected 51 cases with increased, 4 with decreased and 5 with normal temperature. Sonography examination was positive for 45 cases and negative for 12 cases. Sonography had a positive sonograms rate of 71% for clinical diagnosis.	Infrared imaging is sensitive in the cases of epicondylitis and can complement morphology based imaging with information on the acuteness of morphological alterations.	Research on the existence of a relationship between temperature and the time passed since the onset of injury is needed.
Rossignoli et al. (2016)	Relationship between Shoulder Pain and Skin Temperature Measured by Infrared Thermography in a Wheelchair Propulsion Test	To analyse skin temperature variations, caused by wheelchair propulsion test (T-CIDIF), in athetic wheelchair users, to assess the relationship between shoulder pain (SP) and temperature asymmetry (ΔTsk) and to relate the SP with the T-CIDIF.	12 wheelchair user athletes performed the T-CIDIF in their own wheelchair, and the SP was measured with the Wheelchair Users Shoulder Pain Index (WUSPI). The exercise consisted in a 30 s maximum test performed on two rollers. Skin temperature of anterior and posterior upper body was acquired, before and after T-CIDIF, by the infrared camera FLIR T335.26 regions of interest (ROIs) were evaluated (anterior and posterior Arm, anterior and posterior Shoulder, anterior and posterior Forearm, Pectoral, anterior and posterior Trapezius, Dorsal, Infraspinatus, Supraspinatus and Central Trapezius).	There were significant differences between the Tsk of the post-10 and pre-test in 12 ROIs, and between the post-10 and the post-test in most of the ROIs. These differences are attenuated, when the ΔTsk is compared before and after exercise. Tsk tends to initially decrease immediately after the test and then significantly increase after 10 min of completing the T-CIDIF. The ΔTsk vs SP analysis yielded significant inverse relationships	Results suggest that high performance whellchair athletes have similar capacity of heat production to that of the able-bodied. Moreover, thermographic data correlates negatively with the SP and the T-CIDIF variables. The SP results don't correlate with the TI-CIDIF ones.	Further studies with larger samples and with broader populations should be conducted, so that more causal relationships can be established.
Neves et al. (2016)	The thermal response of biceps brachii to strenght training	To determine the relationship among exercise volume and the time/intensity of thermal response during biceps brachii exercise and on subsequent days.	The volunteers were randomized into 2 groups: 3BS (15 subjects), that did 3 sets of 16 repetitions of biceps exercise with dominant arm, and 5BS (13 subjects), that did 5 sets of the same exercise. Thermal images of the arm region were recorded (using the IR	The temperature of the biceps regions decreased in both groups, during the first minute of exercise. During most of the exercise, the temperature of the control group tended to decrease and the temperature of the exercise group tended to increase. The temperature values of the control group followed the values of	There was a strong relationship among exercise volume and time/intensity of thermal response after exercise. Temperature of contralateral arm goes along with the exercise arm temperature at subsequent days after exercise, and the thermal	–

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Table 1 (*continued*)

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			camera FLIR SC2000) before the exercise, and after each sets, and at 24, 48, 72 and 96 h after exercise.	the exercise group on the following days. The temperature changes lasted for over 4 days in the exercise group. The thermal response did not show significant statistical correlations with delayed onset muscle soreness scores.	effects last for more than 4 days after high exercise volume.	
Aguilar et al. (2016)	Development of a Mechatronic Device for Arm rehabilitation With Medical Infrared Thermography Evaluation	To use medical infrared thermography as a method of evaluation of health recovery for elbow rehabilitation.	A mechatronic device for elbow rehabilitation routine was tested in one healthy participant. During the use of the rehabilitation device, an IR camera FLIR E50 was used for thermographic evaluation of arm and forearm muscle and blood vessel regions.	After the use of the mechatronic device, a rise in temperature was observed in the peripheral blood vessels and exercised muscles of the arm and forearm.	The results indicate that Infrared thermography might permit the evaluation routine elbow rehabilitation and recovery, through temperature evolution analysis.	Further studies, with significant amount of participants (and with certain pathologies affecting the elbow joint) will be required to assess the mechatronic device viability.
Reste et al. (2015)	Wrist Hypothermia Related to Continuous Work with a Computer Mouse: A Digital Infrared Imaging Pilot Study	To assess the dynamics of skin temperature in the hand during computer mouse work in different ergonomic setups.	Digital infrared imaging of the right forearm of and wrist of 4 healthy young people were applied, during 3 h of computer work. Thermographic measurements were done at the start and every 15 min until the end of the examination, in 3 different days, using the IR camera ICI ETI 7320 Pro. Each examination day had a different computer mouse setups: horizontal mouse without pad, horizontal mouse with pad and vertical mouse without pad.	Skin temperature of the hand and forearm decreased 1 h after computer mouse work. The use of vertical computer mouse preserved more stable and higher temperatures of the wrist (> 30 °C), while 2 h of horizontal mouse use caused extremely low temperature (< 28 °C) in distal parts of the hand.	The results of the study indicate the existence of a significantly strong negative correlation between the temperature of the dorsal surface of the wrist and time spent working with a computer mouse. These preliminary findings show the potential considerable importance that ergonomics of the computer mouses has on the development of hand hypothermia.	Further larger studies should be conducted to investigate the thermal effects of prolonged use of computer mouse, under different ergonomic settings and with controlled environmental conditions.
Novotny et al. (2015)	The influence of breaststroke swimming on the muscle activity of young men in thermographic imaging	To describe and assess energetic-metabolic activity of selected muscles of upper extremities and body during breaststroke swimming throught infrared thermography.	Thermograms of 25 college students were taken (using the thermal camera FLUKE TiR) immediately and 15 min after swimming 1000 m focused on 20 regions of interest, corresponding to selected agonistics and synergists in the upper extremities and upper body.	There was a significant increase 15 min after swimming in triceps brachii, and in side, rear and front parts of the deltoid muscles. The swimming exercise contributed to a significant increase in the temperature of ROIs of upper limbs (but a significant temperature decrease ocurred in body muscles).	It can be concluded that swimming 1000 m breaststroke promotes significant rise in the temperature of regions corresponding to agonists and synergists of upper extremities for the swimmer's forward motion. A relative fall in temperature occurred in the upper body muscles.	The accuracy of thermographic evaluation of muscular activity could be researched in the future.
(Neves et al., 2015b)	The influence of subcutaneous fat in the skin temperature variation rate during exercise	To investigate the influence of subcutaneous fat layer in the skin temperature variation rate, during exercise.	17 Healthy participants, divided in 2 groups (GP1, with biceps brachii skinfold thickness < 4 mm, and GP2 with thickness between 4 and 8 mm), performed 3 sets of 16 repetitions of biceps exercise with the dominant arm. Thermograms were taken by the thermal camera FLIR SC2000, during the exercise.	The skin temperature variation rate was 3.59 × 10–3 ± 1.47 × 10 - 3 °C/s for GP1 and 0.66 × 10–3 ± 4.83 × 10 - 3 °C/s for GP2. Subcutaneous fat layer also influences the skin temperature at resting. Participants with smaller subcutaneous fat layer have a higher skin temperature variation rate.	Results suggest that subcutaneous fat layer serves as a thermal barrier against muscle heat dissipation and that individuals with smaller layers tend to have higher skin temperature variation rates, during exercise, than those with a greater one.	Further research on the study of the inclusion of subcutaneous fat layer as a covariable should be conducted, since it influences the heat transfer rate from the muscle to the skin surface.
Neves et al. (2015a)	Influence of Muscle Cross-sectional Area in Skin Temperature	To determine the correlations among arm subcutaneous fat percentage, arm muscle cross-sectional area, arm total scross-sectional area, and the difference between core and	Skin temperature was measured by acquisition of thermal images of 20 healthy volunteers. The thermal camera used was the Fluke-Ti10, and the regions of interest were the biceps and	It was possible to observe significant correlations between muscle areas and the Δ temperature for Biceps, but the same was not encountered in the triceps muscles. The biceps skinfold seems to be less than the triceps, permitting for	Results confirmed that arm muscle cross-sectional area influenced skin temperature at the biceps region, which can be generalized to other regions that	–

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		skin temperature (Δ) in biceps and triceps areas, using infrared thermography.	triceps regions. The core temperature (Tc) was measured throught tympanic temperature, a Braun Thermoscan infrared ear tympanic thermometer. For anthropometric measurement, it was used an adipometer and a stadiometer.	thermogenic effects within the biceps. Although, for the triceps, the heat dissipation is more limited by a greater presence of a fat layer.	show similar characteristics to the examined zone.	
Magalhaes et al. (2015)	Evolution of Skin Temperature after the Application of Compressive Forces on Tendon, Muscle and Myofascial Trigger Point	To determine the ideal time of performing thermographic examination after palpation based on the assessment of skin temperature evolution.	The IR camera FLIR T300 was used for arm (myofascial trigger joint and biceps brachii muscle) temperature measurement before and after the application of compressive forces (15, 30, 45 and 60 min). 15 healthy computer user volunteers were examined. A digital dynamometer was used for the application of the compressive forces.	Significant temperature decrease was observed (30, 45 and 60 min after the application of compressive forces) on the palmaris longus tendon and biceps brachii muscle.	After assessment or diagnosis methods, which make use of force application on muscle and tendons, have been performed, infrared thermography can be applied 15 min after contact with the skin (60 min after the procedure for thermographic examination of the myofascial trigger point).	Research should be conducted on the use of infrared thermography and palpation in other pathological conditions, as long as their combination is clinically applicable.
Lampe et al. (2015)	Thermograpic study of upper extremities in patients with cerebral palsy	To evaluate the temperature regulation of the upper limbs of young adults with different forms of cerebral palsy (CP).	22 patients with CP and 6 healthy subjects participated in this study. Their dominant upper limb was examined. The hand force was recorded with a conventional dynamometer and its hand volume with a volumeter. A cold stress test was also performed. The warming up process (forearm and hand) was done with IR camera BCAM SD, before and after (every 30 s over 1 h period) the cold test.	Results support correlation between forearm/hand volume and grip force, and between grip force and warm up time. No correlation between forearm/hand volume and warm up time. Healthy control group had a better thermal recovery than those with cerebral palsy.	The extent and speed of temperature regulation of the subjects with CP are confirmed to be below than those of the healthy group. The findings also approve the notion that the ability to regulate periphery temperature is dependant of the motor skills.	–
Haluzan et al. (2015)	Thermal changes during healing of distal radius fractures - Preliminary findings	To determine the temperature difference between healthy and fractured forearm and the dynamics of thermal changes during bone healing.	Thermographic recordings (using the FLIR ThermaCam B2 IR camera) of the forearms of 25 patients were conducted 1, 3, 5, 11 and 23 weeks after fracture of the distal radius. The contralateral healthy forearm was used for comparison.	After fracture, the mean temperature difference between healthy and fractured distal forearm was 1.20 ± 0.48 °C (1 weeks), 1.42 ± 0.54 °C (3 weeks), 1.04 ± 0.53 °C (5 weeks), 0.50 ± 0.30 °C (11 weeks) and 0.22 ± 0.25 °C (23 weeks).	The preliminary results show significant temperature changes during the healing of distal radius fracture. Infrared thermography could be a viable follow-up method in traumatology.	It is planned to conduct measurements on a larger number of patients and to extends future investigations on other fractures.
Ćurković et al. (2015)	Medical thermography (digital infrared thermal imaging - DITI) in pediatric forearm fractures - A pilot study	To measure the difference, dynamics and duration of temperature changes during pediatric forearm fracture healing.	Radiographic scans and thermographic measurements (using the IR camera FLIR ThermaCAM B2) of forearm with fracture and of healthy forearm of 19 patients were taken and compared 7, 14, and 21 days after injury (and 28 days if there was a temperature discrepancy more than 21 days).	The thermograms showed that the temperature of the fracture forearm was higher than that of the healthy forearm. The highest temperature difference between fracture and healthy forearms was from 0.8 °C to 2 °C (7 days after injury), from 0.4 °C to 1.4 °C (14 days after injury) and from 0 °C to 0.7 °C (21 days after injury).	Results show that there is a noticeable temperature difference between broken and healthy forearm (observable by infrared thermography). Infrared thermography may be implemented during standard healing follow-up, which may help reduce the frequency of exposure to x-rays.	Studies with more temperature measurements and patients will provide results with less error, better results, and provide relevant temperatures that correlate with bone healing process seen on plain radiography.
Chang et al. (2015)	Rapid vs delayed infrared responses after ischemia reveal recruitment of different vascular beds	To assess blood flow dynamics in healthy subjects forearms using IR imaging.	A Post-occlusive reactive hyperemia (PORH) test (a standard test of circulatory function) was used alongside infrared thermography of the	The majority of the forearm volar surface remains unaltered during occlusion-reperfusion and, therefore, it is not amenable to quantification of the reactive hyperemia. Although, by	Continuous infrared imaging revealed transient changes in forearm temperature during arterial occulation, reperfusion and recovery in a healthy subject	Further studies are needed to understand the anatomical differences between reactive and non-reactive vasculature, and to analyse the

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			volar aspect of the forearms of 38 healthy volunteers. IR recording (using the IR camera Santa Barbara FocalPlane Array) was validated by comparing it with the blood flux values, using laser Dopper flowmetry probes.	applying a k-means partitioning method for identification of the forearm thermally reactive areas, it was possible to quantify the magnitude and duration of reactive.	group. Thermography may be used as a navigational tool for the positioning of point measurement sensores on areas of the human skin that are particularly sensible to vascular perturbation.	physiological factors that can influence the temperature dynamics of the forearm.
Boguszewski et al. (2015)	Impact of classical massage on temperature, strength and flexibility of upper limbs muscles in healthy men	To characterize the dependence between application of classical massage of hand and forearm and the temperature of muscles surface of the upper limb and the strength of hand and the range of motion in radio-carpal joint.	12 young and healthy participants underwent a forearm thermographic examination, using the Flir A325 IR camera. Hand strength was assessed by an analog dynamometer, and the range of motion in radio-carpal joint was determined by a goniometer. All measurements were conducted twice (before and after the massage of hand and forearm of the dominant upper limb).	After the massage, the skin temperature of the upper limbs rose considerably. Although, there was no significant changes of temperature of the front surface of the left forearm. There were no significant differences in the hand strength, before and after massage.	Even though classical massage promotes the rise of temperature of the muscles, it is not a sufficient means for physical effort preparation. Due to massage, the range of motion in the joint of massaged limb appears to have been broadened.	Results are basis for continued research on greater and more diverse groups.
Ratovoson et al. (2013)	Influence of gravity on the skin thermal behavior: experimental study using dynamic infrared thermography	To highlight quantitatively some effects of blood flow on the heat diffusion.	A cylindrical steel bar cooled or warmed was put on the skin of forearm of 2 healthy volunteers, and the temperature change was measured, using the IR camera IRFPA Cedip 560 Titanium. The thermographic measurements were performed in different positions of the forearm (upward vertical, downward vertical and horizontal position).	Influence of blood circulation in veins on the diffusion of temperature was observed. The return to thermal balance is faster, when the arm is in a horizontal position.	The impact that the blood flow of the veins have on skin temperature, in different forearm, was observed. Infrared thermography was a viable method in the assessing of the temperature changes due to blood flow variation.	This work provided a database that can be used for the validation of predictive thermal models of human skin.
Abate et al. (2013)	Comparison of cutaneous thermic response to a standardised warm up in trained and untrained individuals	To quantitatively evaluate, by means of infrared thermography, the differences in the cutaneous temperature among trained and untrained subjects	40 male volunteers performed a standard warm up exercise on a stationary cycle, divided in three steps: 1) 0–5 min at 100 Watt; 2) 5–10 min at 130 Watt; and 3) 10–15 min at 160 Watt. Thermal images were taken with a FLIR SC3000 infrared camera from thorax and upper limbs were collected during the exercise. Heart rate was also measured.	Trained subjects exhibited a significant temperature reduction in the third step, while no difference was observed in untrained subjects. In the comparison between groups, a statistically significant difference was observed in both regions of interest, in the second, and in the third. During the whole exercise, heart rate increased progressively in all participants, but more markedly in untrained subjects.	Cutaneous thermoregulatory response differs among trained and untrained participants. Infrared thermal imaging is useful in detecting these differences, providing additional data to the physiological evaluation of subjects performing sport activities.	Individual physical fitness was not assessed (e.g. VO2 max consumption).
Trentin et al. (2012)	Thermography: an assessment tool in the Ergonomic Analysis of a Work Station in the Foundry Industry	To explore thermography as a means to make an ergonomic evaluation of a job in metal casting.	During a macro-ergonomic analysis in a medium-sized industry, thermograms (using the IR camera FLIR InfraCam) of the arm, forearm and hand regions of 27 workers were recorded, during their work activity.	An increase of 1.8 °C in the average skin temperature of the regions examined was observed, before and after 1.5 h of work activity. This temperature variation indicates that a great physical exertion was applied in the workplace.	The analysis of the acquired thermograms suggests that infrared thermography can assist in the evaluation of work activites that involve physical exhaustion and aid in the study and improvement of jobs in the industry.	Reference values should be sought to assist in the analysis of thermograms before, during and after the physical activities demanded in work tasks.
Silva et al. (2012)	Early assessment of the efficacy of digital infrared thermal imaging in pediatric extremity trauma	To assess the efficacy of digital infrared thermal images (DITI) in pediatric extremity trauma.	Thermograms of 51 patients with forearm trauma (who underwent an extremity radiography exam) were taken (through the IR camera Meditherm med2000	DITI matched 73% of the pain sites. Fractures were observed in 11 sites of the forearms and DITI matched 7 of this 11 fracture sites (63%).	Despite being suboptimal, DITI seems to be a viable method for identification of site injuries, and further evaluation with larger cohorts is encouraged.	Further research would be needed focusing on alternative preparation methods, to make DITI

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			Pro), and the warmest area of each image was compared to the site of pain and/or fracture on the radiograph.			practical for use in a busy emergency department.
(Chudecka and Lubkowska, 2012)	The Use of Thermal Imaging To Evaluate Body Temperature Changes Of Athletes During Training And A Study On The Impact Of Physiological And Morphological Factors On Skin Temperature	To investigate the temperature changes of specific body surfaces (arm and forearm), due to a 90 min exercise, and to analyse the impact of physiological and morphological factors on the dynamics of temperature variation.	A group of 12 professional volleyball players were subjected to a 90 min training session, and the mean temperatures of the upper extremities were taken before, immediately after, and 10 min after exercise, using the thermal camera FLIR SC500. Respiratory rates were measured using an Oxycon Alpha analyzer.	After exercise, the temperature changes were found to be greater on the front surfaces of the upper extremities, when compared to the rear. There was a strong influence of maximum oxygen uptake on the fall of temperature of the upper limbs.	Results suggest that thermography can be a complementary method that can provide information about the players fitness level.	–
Bartuzi et al. (2012)	The Influence of Fatigue on Muscle Temperature	To investigate the possibility of using infrared thermography for assessing muscle fatigue during low effort.	Thermographic measurements, during biceps brachii (BB) exercise in 10 healthy college students, was conducted. The chosen thermal camera was the ThermaCAM FLIR SC2000. BB force was recorded by dynamometer and its EMG signal.	Constant load sustained during the tests resulted in an increase in the temperature of biceps brachii.	Results suggest that IRT can be an alternative or supplementary method for assessing muscle fatigue at low levels of contraction.	–
(Al-Nakhli et al., 2012b)	The Use of Thermal Infra-Red Imaging to Detect Delayed Onset Muscle Soreness	To assess the usefulness of thermal IR imaging in detecting and measuring muscle soreness (biceps brachii) after strenuous exercise.	Arm muscle strenght was measured throught the use of a strain gauge device (3 measurement, where each contraction lasted 3 s). Thermal Recording of the arm of 41 healthy subjects was done by the thermal camera FLIR 660 IR, at different angles and different distances (before exercise, 24 h and 48 h after).	Images obtained at the 3 time periods showed a noticeable increase in temperature on day 2 (24 h post-exercise) when compared to pre-exercise temperatures, and temperatures taken at 48 h after. Un-exercised arm, changes were not evident.	Results suggest that IR imaging could be a valid technique for detecting delayed onset muscle soreness (DOMS), especially within the first 24 h after exercising. There was a close relationship between the increased skin temperature and the increased muscle soreness.	The early detection of DOMS (with the help of IR thermography) could be useful in lowering injuries from over-exercised muscles, in the sport setting.
Al-Nakhli et al. (2012a)	The Use of Thermal Infrared Imaging to Assess the Efficacy of a Therapeutic Exercise Program in Individuals with Diabetes	To investigate temperature changes in abdominal and biceps muscles (by infrared thermography), in order to observe the influence of Delayed-onset muscle soreness (DOMS), common in people with diabetes.	2 groups of subjects (62 healthy participants and 66 with diabetes) performed a biceps exercise. Skin temperature in the arm muscle regions was measured 24 h post-exercise, by the IR camera FLIR TC660, and muscle soreness was assessed by 100-mm visual analog scale. Serum myoglobin concentrations were also measured.	It was observed a significant increase in skin temperature 24 h after arm exercise. The groups were also significantly sorer than they were at baseline. Moreover, serum myoglobin levels were also significantly higher on day 3 compared with the first day.	Infrared thermography may be useful for identification of sore muscles, hours or days after exercise, in both healthy subject or with diabetes.	–
Mohamed et al. (2011)	Assessment of Piano-Related Injuries using Infrared Imaging	To examine the difference in hand and arm temperatures of pianists with and without pain related piano-playing.	Thermal images (hand, forearm and arm regions) of 9 musicians (3 of them without piano-related pain) were taken by an IR camera FLIR 320 M, during 3 examinations: two sets of 10 min piano exercise at grade 4 level of piano; 10 min to play four octaves at 112 beats per minute and 5 min octave scales.	Pianists with pain were found to be statistically different from the musicians without pain, based on the mean temperature measurement of the hands. There was a statistically significant difference in hand temperatures between the two populations, but not in the forearm and arm temperatures.	The research results confirmed that the protocol is an adequate template for further studies with pianists and other musicians.	It will be beneficial to perform image analysis of patients without pain early in their music career, in order to assess if they develop pain related to piano-playing.

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Reference	Title	Aim	Methodology	Major Results	Conclusions	Open Challenges
Lange et al. (2011)	Skin temperature measured by infrared thermography after specific ultrasound-guided blocking of the musculocutaneous, radial, ulnar, and median nerves in the upper extremity	To verify if skin temperature (Ts) would increase after specific nerve blocking in the upper limb.	A FLIR Thermovision A320 camera was used to record and measure Ts in the forearm and hand, at 2 min intervals until 22 min, of 46 patients who underwent nerve blocking of either musculocutaneous, radial, ulnar or median nerve.	The blocking of the ulnar and median nerves promoted a substantial increase in the average Ts of the regions of forearm and hand innervated by these nerves. The rise in temperature was more prominent in the fingertips. Median nerve blocking also increased Ts in the area of the hand innervated by the radial nerve. There was no rise of the Ts in the forearm and hand after blocking the musculocutaneous or radial nerve.	Specific blocking of the ulnar and median nerve promotes substantial increases in Ts in certain regions of the hand. However, the specific blocking of the musculocutaneous or radial nerve does not affect Ts.	Further studies are needed to clarify if these findings can be used to objectively evaluate brachial plexus block sucess.
(Chudecka and Lubkowska, 2010)	Temperature changes of selected body's surfaces of handball players in the course of training estimated by thermovision, and the study of the impact of physiological and morphological factors on the skin temperature	To assess the temperature changes in the selected body surfaces (upper extremities—arm and forearm) in response to directed 90min physical exercise as well as to analyse the impact of physiological and morphological factors on the dynamics of temperature changes.	16 professional handball players, submitted to an endurance training which lasted 90min and contained elements of the actual game in a sports hall with air temperature of 20 °C and air humidity of 55%. The mean temperatures from chosen body surfaces were registered before, immediately after and 10min after physical effort (90min) in comfort temperature conditions by means of a thermoviosion (ThermaCAM TM Sc500 camera).	Strong and statistically significant influence of maximum oxygen uptake on the loss in surface temperatures in upper arm and forearm immediately after the exercise indicates that thermography can be used as an additional, non-invasive method to provide information on the level of a player's fitness in comparison with the rest of their team.	The front upper and forearm surfaces seem to be more appropriate body areas to assess the dynamics of temperature Changes, since these areas have poorer lower adipose tissue and thus less effective thermal insulation preventing heat to be lost, which makes it easier to determine the temperature changes.	–
Sefton et al. (2010)	Therapeutic Massage of the Neck and Shoulders Produces Changes in Peripheral Blood Flow When Assessed with Dynamic Infrared Thermography	To determine the effects of therapeutic massage on peripheral blood circulation, throught dynamic infrared thermography.	17 healthy volunteers were subjected to 20 min massage on the neck and shoulder, and the mean surface temperature of 15 regions of the neck, upper body, arm, forearm and hand were recorded by the IR camera Computerised Thermal Imaging Inc Ogden UT (at pretest, 15, 25, 35, 45 and 60 min post-test).	The massage promoted significant increases in temperature in five regions: anterior upper chest, posterior neck, upper back, posterior right arm, and middle back. Also, the temperatures stayed above baseline levels after 60 min.	Results suggest that massage promoted peripheral blood flow changes in the treated areas as well as in adjacent not-massaged areas, culminating in temperature alterations. Dynamic infrared thermography might be a viable tool for the a noninvasive, noncontact measurement of the peripheral blood flow changes, during massage therapy research.	A replication of the study with greater sample size and the exploration of the diverse physiologic response to therapeutic massage (using thermography) is encouraged.
Merla et al. (2010)	Thermal Imaging of Cutaneous Temperature Modifications in Runners During Graded Exercise	To observe anterior cutaneous temperature variations in trained runners during graded exercise.	15 runners performed a graded treadmill exercise, until each participant reached their max heart rate, and thermograms of the forearm and thighs were captured, during the exercise, so that the cutaneous temperature (Tc) distribution could be observed. Thermal images were acquired with the IR camera FLIR SC3000, and heart rate was measured with electrodes.	Forearm and thighs showed the earliest increase, followed by total body Tc rise. It was possible to observe hyperthermal spots, due to the presence of muscle perforator vessels during baseline and recovery (not during exercise).	Results indicate that infrared thermography allows the characterization of specific cutaneous whole body thermal adaptations, during and after graded physical activity.	Further studies could be conducted on the evaluation of local and systemic cutaneous blood flow adaptation as a function of specific type, intensity and duration of exercise, so that the ideal conditions for physical activity can be assessed.
Park et al. (2007)	The effectiveness of digital infrared thermographic imaging in patients with shoulder impingement syndrome	To evaluate patients with shoulder impingement syndrome using digital infrared thermography imaging (DITI) for objective detection of	An IR camera IRIS 5000 was used to measure the temperature of 100 patients, diagnosed with shoulder impingement syndrome. Thermograms from the upper	In DITI findings, 73% of patients had abnormal thermal changes. 51% displayed hypothermia (with more shoulder limitation) and 22% had hyperthermia. There was a greater	DITI can be used to reflect shoulder stiffness objectively in impeginment syndrome, especially in those cases with a hypothermic thermal pattern.	To clarify the effectiveness of DITI, patients with impingement syndrome need to be followed up after surgical management.

(*continued on next page*)

Table 1 (*continued*)

Reference	Title	Aim	Methodology	Major Results	Conclusions	Open Challenges
		shoulder pain and limitation, and to reveal any other relationship among clinical, physical or operative findings and DITI.	body and upper extremities regions (shoulders, arm, forearm and hand) were recorded. The relative temperature values between involved and uninvolved sides was used for analysis. A control group of 30 participants without impingement syndrome was also evaluated.	limitation of the shoulder motion in the hypothermic group than in the hyperthermic and normal groups.		
Jaworski et al. (2007)	Arm temperature distribution in thermographic pictures after radial artery harvesting for coronary bypass operation	To assess arm temperature changes after removal of the radial artery and determine whether there is an effect on hand function.	Thermographic measurements of forearm and hand of 15 patients, that underwent coronary artery bypass grafting (with radial artery harvesting), were conducted using the Agema Thermovision System 900SWyTE camera. A handgrip test was also performed, before and after surgery, using a hand-help dynamometer.	Before radial artery harvesting, the fingers temperature decreased after the handgrip test. After radial artery harvesting, similar temperature variations were observed after exertion. In contrast, the resting temperature was lower than the temperature before the surgery.	The research suggests that radial artery removal affects the hand skin temperature, but not the hand function in the short-term. Also, the radial artery harvesting did not cause clinically relevant changes in the blood circulation of the arm.	A long-term follow-up with thermography examination is needed in patients after radial artery harvesting in order to assess changes in hand and forearm perfusion.
(Herry et al., 2005)	Evolution of the Surface Temperature of Patients's Arm Muscles Using Infrared Thermography	To study the effects of an arm warm-up on the performance of musicians, during piano practice.	Thermal images of the hands, arms, forearms, neck and face of 8 pianists were taken (using the FLIR ThermaCAM SC500), during piano practice session, every 15–20 min.	The evolution of the arm skin temperature varies significantly between pianists. This evolution with a slow general decrease of the temperature over the practice and, then, there is an abrupt decrease in the middle of the exercise.	Results suggest that thermography can distinguish different levels of impact that the playing techniques have on the musicians' muscles.	A controlled study of warm-up procedures and the respectives effects will be conducted, in order to understand the changes in temperature of the first study.
Galvin et al. (2006)	Thermographic Temperature Measurement Compared with Pinprick and Cold Sensation in Predicting the Effectiveness of Regional Blocks	To evaluate the usefulness of thermographic temperature measurement as a mean to assess the sucess or failure of axillary blockades.	25 patients underwent axillary blockage operation in one of the upper limbs. Thermograms (acquired by the IR camera FLIR SC2000) of the forearm and hand regions of the operated limb were recorded every 5 min for 30 min. Thermograms of the not operated extremity were recorded before the operation and 30 min after. Pinprick and cold sensation were assessed on the operated site at 5 min intervals for 30 min.	Infrared thermography had higher combined values of sensitivity, specificity, positive and negative predictive values than both cold and pinprick at all time intervals, with statistically significant differences at 15 min and 30 min.	Successful axillary block is associated with an increase in temperature (forearm) in the anesthetized dermatomes. A faliedblock is not associated with a temperature increase. Thermography provides an early and objective assessment of the success and failure of axillary regional blockades.	Further studies are necessary to establish the specificity, sensitivity, and predictive values of thermography in assessing other types of regional blocks.
Thomas et al. (1992)	Computerised infrared thermography and isotopic bone scanning in tennis elbow	To compare infrared thermography with isotopic bone scanning and defining parameters that may be of diagnostic value in tennis elbow.	Thermal assessments (arm, elbow and forearm) of 26 patients (diagnosed with tennis elbow) were made with an Agema 782 camera. The patients also underwent isotopic bone scanning	A hot focus was visualised in 16 of 17 cases of unilateral tennis elbow (94%) and in all nine cases of bilateral tennis elbow (100%) on infrared thermography. Abnormal increase in epicondylar activity was observed in 12 of 17 cases (71%) and 8 of 18 cases (44%), respectively, with isotopic bone scanning. Unilateral visual cooling occurred in 7 of 13 cases of unilateral tennis elbow (54%) with infrared thermography, and there was reduced perfusion in 7 of 12 (58%) of similar cases with blood pool isotopic bone scanning.	The study shows that infrared thermography is a sensitive objective investigational procedure for the assessment of unilateral and bilateral tennis elbow.	–

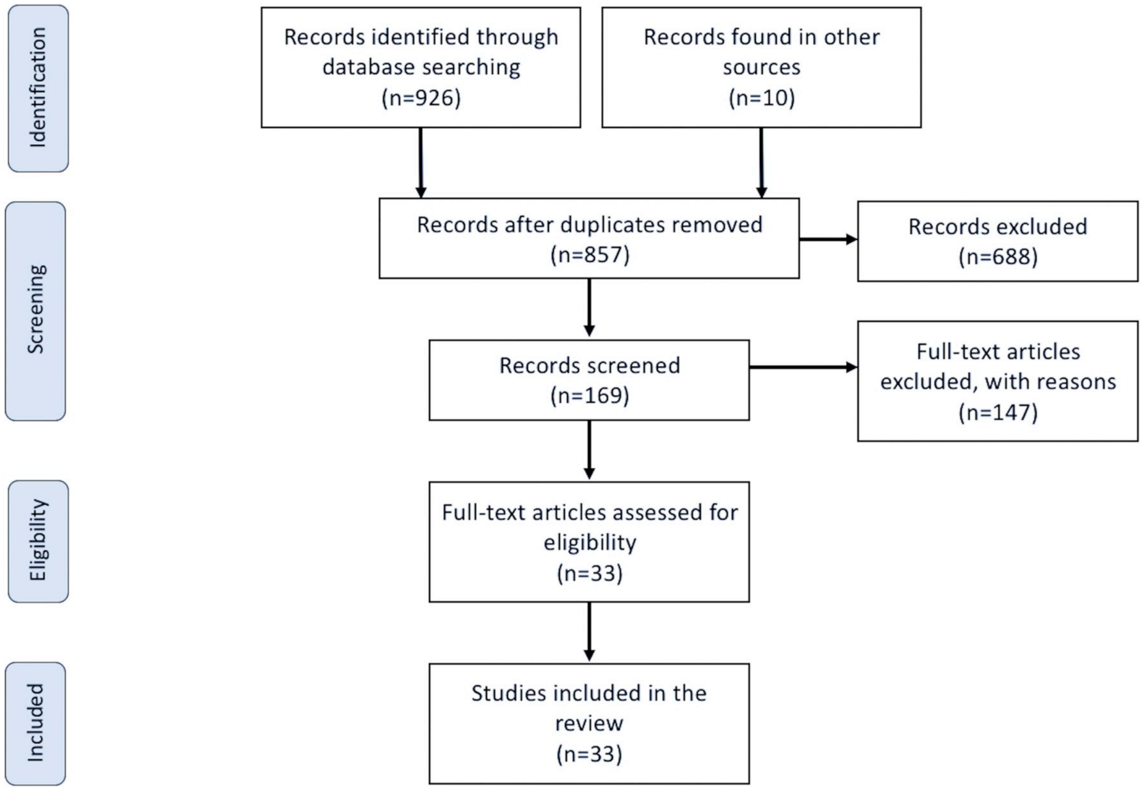

Fig. 1. PRISMA flow diagram, based on (Moher et al., 2009).

inflammations, peripheral vascular diseases and neurological (Gatt et al., 2015) and musculoskeletal disorders (Sanchis-Sánchez et al., 2014).

Monitoring of the upper limbs, specifically arms and forearms, is gaining importance to characterize subjects' health status and determine levels of frailty and senescence in medical legal situations (Bohannon, 2008).

The aim of this systematic review is to identify the outcomes and proposed further research lines of biomedical musculoskeletal applications of IRT in the arm and forearm, mainly in physical evaluation, to aid new experiments, major developments and contribute for a wider acceptance and use of this imaging technique.

2. Methodology

2.1. Search strategy

The literature review was performed using the source engines PubMed and Scopus. The articles were found with the specific combination of keywords: (Infrared Thermography OR Thermal Imaging OR Infrared Imaging) AND (Arm OR Forearm). The key terms "Infrared Thermography", "Thermal Imaging" and "Infrared Imaging" are frequently applied interchangeably, so the Boolean operator OR was used to include all terms. Time restriction was not considered, but this literature survey was finalized in July 2018.

2.2. Screening and eligibility

Considering the title and abstract of each identified article, only records that reported the application of IRT in the arm and forearm were selected for screening.

During this process, two types of articles were removed: duplicates and inadequate articles. Those considered inadequate were not in line with the following eligibility criteria. The first criterion was that the article must apply IRT for the measurement of the arm and/or forearm skin temperature. Secondly, it needs to conduct research that strives for biomedical applications. Then, other modalities of thermography (such as liquid crystal thermography) are not considered. Lastly, reviews and articles with foreign language (not in English) are also not included.

2.3. Papers assessment and scoring

In order to provide an objective assessment on the quality of the surveyed papers, a thermographic imaging in sports and exercise medicine (TISEM) checklist (Moreira et al., 2017) is applied. The aspects of subject data, previous instructions, environmental conditions, image background, acclimation, camera preparation, extrinsic factors, environmental setup, equipment, image recording procedure, camera position, emissivity value, body position and image evaluation are graded, with each point taking the value of: no (0), unclear (1) or yes (2). At the end the score is summed, being 30 the maximum value that can be obtained and 1 the minimal. The level of evidence is also assessed by the proposed scale of Sackett (Burns et al., 2011), which has 5 levels, ranging from large randomized controlled trials (RCT) with clear cut results (I), small RCTs with unclear results (II), Cohort and case-control studies (III), Historical cohort or case-control studies (IV) and Case series, studies with no controls (V). The existence statistical analysis of the papers is also appraised in terms of means comparison (basic), and variation and correlations (advanced).

3. Results

After a literature database search, a total amount of 926 articles were identified for screening, being 468 articles from PubMed search and 458 acquired through Scopus engine. An additional 10 articles were found through Google Scholar. From the total amount of 935 identified articles, 78 duplicates were removed and 857 articles were approved for the next screening phase. In the remaining 857 articles, 680 were not in line with the aim of this review, and 8 articles were unavailable online. Therefore, 169 articles were deemed adequate for eligibility and from those a total of 147 articles were discarded due to nonfulfillment of the defined eligibility conditions. At the end, 33 articles were analyzed and included in the review. Each article is found characterized by aim, methodology, main results, conclusions and open challenges in Table 1. The results were divided in three main topics based on the context in which IRT is used for the assessment of arm and forearm skin temperature: physical condition evaluation, health recovery monitoring and complementary tool for pathology assessment. The several steps used for the literature review are displayed in the following PRISMA flow diagram illustrated in Fig. 1, according to the PRISMA guidelines (Moher et al., 2009).

3.1. Physical condition evaluation

IRT has been a subject of research for arm and forearm physical condition assessment. One of the most explored setting of analysis in the upper limbs, using IRT, is research focused on the influence that arms muscle exertion has on the surface temperature distribution of the extremity. In fact, several authors (Neves et al., 2016; Al-Nakhli et al., 2012b; Herry et al., 2005) concluded that IRT may be an asset in the evaluation of arms muscles fatigue. Researchers observed a close relationship between altered biceps brachii skin temperature region and increased muscle soreness and fatigue. Exploring the arms thermal response to muscle fatigue was also performed in the field of music. According to the results of Herry et al. (2005), obtained from a piano practice session with musician participants, IRT showed to be of value for the assessment of the impact level that piano playing techniques have on the musicians' arms muscles.

Observing temperature disparity between limbs and the effects of muscle dimensions and fat tissue on arms temperature area is another option for physical assessment, using IRT. For instance, a bench-mark of bilateral differences of temperature distribution, in the forearm region, was observed by Vardasca et al. (Vardasca et al., 2018). The results indicate that IRT could be useful in the identification of vascular, neurological and musculoskeletal conditions, through the comparison of bilateral differences between thermal skin patterns of the upper limbs of the same person. Other studies by Neves et al. (Neves et al., 2015b; Neves et al., 2015a), used IRT to record the variation of skin temperature distribution, during the performance of a biceps brachii exercise. It was observed that subjects with lower subcutaneous fat layer had a higher skin temperature variation rate, and that muscle cross-sectional area was influenced by arm muscle region' skin temperature.

IRT has also been applied to study the impact of sport activities in the arm and forearm skin temperature. In Novotny et al. (2015), breaststroke swimming exercise performed by young men, lead to a significant rise in temperature of the triceps brachii muscle region. Also, Chudecka et al. (Chudecka and Lubkowska, 2012) explored the use of IRT in volleyball athletes. It was observed a significant influence of the maximum oxygen uptake on the fall of skin temperature in the arm and forearm region. Moreover, Merla et al. (2010) reported specific anterior cutaneous temperature variations of the forearm, during and after graded exercise performed by well-trained runners.

Furthermore, IRT was applied in the evaluation of methodologies used in arm and forearm physical assessment procedures and ergonomics. For instance, Magalhaes et al. (2015) chose IRT to record the skin temperature evolution of the biceps brachii (in healthy participants) after the application of compressive forces in the muscle. Significant decrease of arms' surface temperature was observed, after using dynamometer as a tool to measure compression force. For ergonomics, Reste et al. (2015) focused on the assessment of forearm surface temperature dynamics of the dominant extremity of young healthy volunteers, during computer mouse work. Forearm skin temperature was found to be negatively correlated with the time spent using the computer mouse. Trentin et al. (2012) conducted a study to explore IRT as a tool for ergonomic evaluation of workers in a foundry industry setting. The imaging modality was successful in the detection of substantial increase of arms skin temperature after an hour and a half of working activity. The authors suggest that IRT could be an adequate technology for quantification of physical activity in a working facility.

A study assessing skin temperature changes in the arm and forearm of handball players, in response to physical exercise, has found strong and statistically significant influence of maximum oxygen uptake on the loss in surface temperatures in the arm and forearm immediately after the exercise. This indicates that thermography can be used as an additional method to provide information on the level of a player's fitness in comparison with the rest of their team. It also demonstrated that the arm and forearm regions are poorer in adipose tissue, easing the detection of skin temperature changes (Abate et al., 2013).

A study focused on the appraising of differences in cutaneous temperature among trained and untrained subjects, when performing a standard warm up exercise on a stationary cycle, demonstrated that the thermoregulatory response differs among the two groups. IRT imaging proved to be useful in the detection of these differences, providing additional physiological data. However, individual physical fitness should also be evaluated and correlated with skin temperature (Chudecka and Lubkowska, 2010).

Lastly, Ratovoson et al. (2013) used IRT to study the influence of gravity and altered blood circulation on forearm skin temperature behavior. After a work mechanical stimulus, it was observed a faster thermal balance restoration when the upper limb was positioned horizontally. In a different experiment, Chang et al. (2015) showed that IRT was viable for the detection of transient changes in forearm temperature variation, in healthy participants, during arterial occlusion, reperfusion and recovery. The results support the possibility of applying thermal imaging as a navigation tool to reveal sites in the upper extremity that are especially sensible to vascular perturbation.

3.2. Health recovery monitoring

Another topic of IRT application in the arm and forearm, is whether its usefulness can be extended to the monitoring of upper limbs' health state changes caused by healing mechanisms or medical procedures (Piper et al., 2015; Ring and Ammer, 2012).

A pilot study by Ćurković et al. (2015) focused on the measurement of temperature variation, during pediatric forearm bone healing. The comparison of radiographic scans and thermograms from both healthy patients and patients with fractured forearm, throughout a month period, allowed the identification of noticeable skin temperature differences between healthy and injured patients. In another pediatric study, Silva et al. (2012), aiming to attest the efficacy of early assessment of extremity trauma, reported a successful matching of 73% of the upper limbs pain sites and 63% of the fracture regions. Additionally, Haluzan et al. (2015) found preliminary findings concerning temperature differences between healthy participants and patients with forearm distal radius fracture. The thermographic results showed significant surface temperature variations during fracture healing process. Both studies support the possibility of applying thermal imaging as a follow-up method in traumatology and assist in the reduction of x-ray exposure.

IRT is slowly becoming a target for research focused on the evaluation of therapeutic massage and rehabilitation methodologies on the arm and forearm. Concerning massages, Boguszewski et al. (2015) found a notable rise in forearm skin temperature, after applying massage in healthy subjects. Sefton et al. (2010) also researched if therapeutic massage of neck and shoulders could promote changes in arms peripheral blood flow, through the analyzes of skin temperature distribution. Significant temperature changes in the posterior arm of healthy participants were found, suggesting peripheral blood flow changes in the massaged areas. For rehabilitation, Aguilar et al. (2016) analyzed temperature disturbance provoked by the use of a developed mechatronic device for arm rehabilitation. A temperature increase was observed in healthy participants, indicating evidence of exertion in the arms muscles and peripheral blood vessels.

Certain medical procedures and therapies induce changes in the integrity of arm and forearm peripheral blood vessels and peripheral nerves, affecting limbs superficial temperature. Regarding upper limbs circulation, Jaworski et al. (2007) acquired skin temperature distribution of arms of patients before and after undergoing coronary bypass operation. A decrease in forearm skin temperature over the radial and ulnar artery region, after the surgery, was observed. For upper extremity peripheral nerves, Galvin et al. (2006) monitored patients who underwent axillary blockages, in order to discriminate patients with successful operations from the failed cases. Successful axillary block was associated with an increase of forearm skin temperature, while the failed procedure did not promote a rise in the limbs surface temperature. Finally, Lange et al. (2011) measured patient's forearm and hand skin temperature after specific ultrasound-guided blocking of the musculocutaneous, radial, ulnar and median nerves of the upper limb. The thermographic images showed that the blockage of the ulnar and median nerves caused significant increase in surface temperature, while temperature remained unchanged for blockage the remaining two.

3.3. Complementary tool for pathology assessment

IRT can be used as a complementary diagnostic method for conditions that affect the arm and forearm (Bos et al., 2017).

This imaging modality has been targeted for its usefulness in the discrimination of subjects with arthropathies (joint diseases). Park et al. (2007) were able to detect abnormal thermal changes in arm of patients afflicted with shoulder impingement syndrome. The authors suggest that IRT could be used as a tool to assess the degree of movement limitation of the shoulder. Thomas et al. (1992) assessed patients with joint conditions, with tennis elbow, founding IRT to be a sensible and objective procedure for the evaluation of joint health state and discriminate those from seriously affected individuals.

Al-Nakhli et al. (2012a) used IRT as an evaluation tool for the assessment of the efficacy of a therapeutic exercise program in patients with diabetes. The image technique was sensible enough to detect and distinguish temperature variations in both healthy participants and those with diabetes, allowing the identification of sore muscles after exercise.

In contrast, in order to assess upper limbs temperature regulation on cerebral palsy patients, Lampe et al. (2015) performed a thermographic evaluation of the forearm thermal recovery, after cold provocation. It was confirmed that healthy participants had a better forearm thermal recovery than the cerebral palsy patients.

Gabrhel et al. (2017) investigated whether skin temperature in the arm and forearm could be an asset in the evaluation of patients with painful elbow. According to the results, IRT had a diagnostic sensibility of 91%. Rossignoli et al. (2016) imaged the anterior and posterior upper body (including arm and forearm) of athlete wheelchair users, and found that thermal data had a negative correlation with shoulder pain variables. Furthermore, Mohamed et al. (2011) investigated if piano playing could affect musicians' arm skin temperature. The temperature values of pianists with pain were found to be statistically different from those without.

3.4. Papers TISEM, level of evidence and statistical analysis assessment

It was possible to verify that none of the 33 studies follow completely the TISEM checklist (Table 2), 3 got more than 20 score points, 22 had between 10 and 20 score points and only 8 had less than 10 score points, the smallest score was 1. When assessing the Sackett level of evidence (Table 2), 15 were at II level, 3 at III level, 1 at IV level and 14 at the V level. This demonstrates that the majority of papers were small RCTs with unclear results and case series, studies with no controls. In terms of statistics, only 8 papers did not report any statistical analysis. From the remaining papers only 2 had basic statistical assessment.

4. Discussion

Trends and future approaches of IRT for arm and forearm health assessment include several challenges, such as conducting thermal studies with larger, broader and more diverse populations, acquire reference data to assist the thermogram analysis before, during and after physical activities and create databases for the validation of predictive thermal models of the human skin (Magalhaes et al., 2015; Chang et al., 2015; Boguszewski et al., 2015; Rossignoli et al., 2016).

Regarding future arm and forearm muscle studies, it is recommended to explore the accuracy of thermographic evaluation of muscular activity and to use the subcutaneous fat layer as a co-variable, since it affects heat transfer rate from the muscle to the skin surface (Neves et al., 2015b; Novotny et al., 2015). Further analysis of the early detection of sore muscles, through thermal imaging, is advised, due to its potential in lowering the chances of athletes suffering from injuries caused by over-exercised muscles in the sport setting (Al-Nakhli et al., 2012).

There is need for further research concerning thermal analysis of arm and forearm traumas. It is advised to include a greater number of patients, in order to determine the adequate specificity of IRT. It is also necessary to identify relevant temperature values that correlate to the healing process observed in x-rays (Ćurković et al., 2015; Haluzan et al., 2015). Aside from better thermal analysis, preparation of alternative methods to make IRT practical in a busy emergency department constitutes a future challenge (Silva et al., 2012).

For the use of IRT in upper limb circulation, future studies ought to concentrate on understanding the anatomical differences between reactive and non-reactive vasculature and to analyse the physiological factors related to the temperature dynamics of the forearm (Neves et al., 2015a). Others should focus on the evaluation of local and systemic cutaneous blood flow, so that the ideal conditions for physical activity can be determined, and to perform follow-up thermographic examination in patients after radial artery harvesting, in order to identify changes in forearm perfusion (Merla et al., 2010; Jaworski et al., 2007).

Larger thermographic studies, under controlled environment and diverse physiologic responses, are encouraged for the research of thermal reaction of the arm and forearm to the prolonged use of computer mouse work and therapeutic massage (Reste et al., 2015; Sefton et al., 2010).

Further studies are needed to clarify the use of IRT as an objective assessment tool for brachial plexus block success evaluation, and to establish the specificity, sensibility and predictive values in the verification of other types of regional blocks (Galvin et al., 2006; Lange et al., 2011).

Moreover, it might be beneficial to conduct future thermal image analysis of pianists' arms and forearms early in their music carrier, in a controlled environment, not only to gain a better understanding of the warm-up processes and their respective effects, but also to assess the development of pain related to repetitive and cumulative tasks of piano playing (Herry et al., 2005; Mohamed et al., 2011).

It would also be of interest to study thermal changes in the forearm during isometric handgrip exercise (Taylor et al., 1989), since it could provide useful information for health assessment.

In terms of TISEM evaluation (Moreira et al., 2017), the papers assessed in this review showed good provision of the individuals' data of the participants, thermal camera used well described in terms of manufacturer and model, and good description of the procedure of evaluating the thermograms and how the temperature values were extracted from the analysis software. The TISEM points, which were poorer in the literature appraised were: the specification of the time between setting the camera on and the images collection for avoiding the startup drift, the mention of the time of the day that the images

Table 2
Revised articles TISEM checklist score (0 – No, 1 – Unclear, 2 - Yes), Sackett level of evidence (I to V) and existence of statistical analysis (A – Advanced, B - Basic).

Reference	TISEM checklist score																Sackett level of evidence	Statistics
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total		
(Vardasca et al., 2018)	2	2	2	2	2	2	2	2	2	2	0	0	2	1	2	25	II	Yes (A)
Gabrhel et al. (2017)	1	2	2	2	1	2	0	0	0	2	2	0	2	0	0	16	II	Yes (B)
Rossignoli et al. (2016)	2	2	2	2	2	2	2	1	2	2	2	2	2	1	2	28	II	Yes (A)
Neves et al. (2016)	2	0	2	2	0	2	0	0	0	0	0	0	0	0	2	10	V	Yes (A)
Aguilar et al. (2016)	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	V	No
Reste et al. (2015)	2	2	2	2	1	1	0	0	1	0	0	0	2	0	2	15	V	Yes (A)
Novotny et al. (2015)	2	0	0	2	0	2	2	0	2	0	0	0	2	0	2	14	V	Yes (A)
(Neves et al., 2015b)	2	0	2	2	0	2	2	0	0	0	0	0	0	0	2	12	V	Yes (A)
Neves et al. (2015a)	1	0	0	1	0	1	2	0	0	2	2	0	0	0	2	11	V	Yes (A)
Magalhaes et al. (2015)	2	0	0	0	2	1	2	0	0	0	2	0	0	0	2	11	V	Yes (A)
Lampe et al. (2015)	2	0	2	2	0	1	0	0	0	0	0	0	1	0	2	10	III	Yes (A)
Haluzan et al. (2015)	2	0	0	2	0	2	2	0	0	0	2	0	2	0	2	14	II	No
Ćurković et al. (2015)	2	0	0	2	0	2	2	0	0	0	0	0	2	0	2	12	II	No
Chang et al. (2015)	1	0	0	2	0	2	2	0	0	2	0	0	2	0	2	13	II	Yes (A)
Boguszewski et al. (2015)	2	2	0	2	2	1	2	2	2	2	2	0	2	0	2	23	V	Yes (A)
Ratovoson et al. (2013)	1	0	2	1	0	6	0	0	2	0	0	0	2	0	2	16	V	No
Abate et al. (2013)	1	0	0	2	0	2	2	0	2	2	2	0	2	0	2	17	II	Yes (A)
Trentin et al. (2012)	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	V	Yes (A)
Silva et al. (2012)	1	0	1	0	0	2	0	0	0	0	0	0	0	0	0	4	V	No
(Chudecka and Lubkowska, 2012)	2	0	1	0	0	1	2	0	2	2	2	0	0	0	0	12	V	Yes (B)
Bartuzi et al. (2012)	2	0	0	1	0	2	2	0	2	2	2	0	2	0	2	17	V	Yes (A)
(Al-Nakhli et al., 2012b)	1	0	1	1	0	1	0	0	2	2	0	2	2	0	2	14	II	Yes (A)
Al-Nakhli et al. (2012a)	2	0	1	1	0	1	0	0	2	2	0	2	2	0	2	15	III	Yes (A)
Mohamed et al. (2011)	1	2	2	1	0	1	2	0	1	2	0	0	0	0	2	14	V	Yes (A)
Lange et al. (2011)	2	0	2	1	2	2	2	0	2	2	2	0	2	0	2	21	II	Yes (A)
(Chudecka and Lubkowska, 2010)	2	0	0	2	0	1	2	0	2	2	2	0	1	0	2	16	II	Yes (A)
Sefton et al. (2010)	1	0	0	1	0	0	2	0	0	0	0	0	1	0	2	7	II	Yes (A)
Merla et al. (2010)	2	1	0	2	0	2	2	0	0	0	0	0	2	0	2	13	II	No
Park et al. (2007)	1	0	0	2	0	1	2	0	1	1	0	0	2	0	2	12	III	Yes (A)
Jaworski et al. (2007)	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	2	IV	No
(Herry et al., 2005)	0	0	0	1	0	1	2	0	0	0	0	0	1	0	1	6	II	No
Galvin et al. (2006)	1	0	0	0	0	1	2	0	0	0	2	0	1	0	1	8	II	Yes (A)
Thomas et al. (1992)	1	0	0	0	0	1	2	0	0	0	0	0	1	0	1	6	II	Yes (A)

were taken, and the drying method used for the skin in the situation that required it, which in most of these applications was not the case. The level of evidence of statistics overall was poor, most research works consisted in small samples, some lacked a control group, 8 papers (Neves et al., 2015b, 2016; Trentin et al., 2012; Chudecka and Lubkowska, 2012; Ratovoson et al., 2013; Chang et al., 2015; Haluzan et al., 2015; Boguszewski et al., 2015) did not presented any statistics and Neves et al. (Neves et al., 2015a) presented the wrong statistics.

IRT has as limitations: providing only temperature information, being an indirect core physiological information; a limited accuracy of ± 2% or ± 1% of the overall temperature reading of the equipment, requiring a controlled environment; results are difficult to reproduce without following a standard capture protocol; relies in proprietary image formats and software analysis tool; absence of DICOM dataset definition; lacks popularity among clinical professionals, despite being the third oldest medical imaging modality.

The advantages or IRT imaging are: fast, easy and relative low cost imaging modality; non-contact, non-invasive and non-ionizing technique; allows imaging of large areas of the skin surface; provides a window to the peripheral nervous system; allows real-time physiology monitoring; provides an indirect assessment of blood flow; allows large scale screening.

Future studies focused on physical assessment of the upper limbs should carefully address in their description aspects of subject data, previous instructions, environmental condition, image background, acclimation, camera preparation, extrinsic factors, environmental setup, equipment, image recording procedure, camera position, emissivity value, body position and image evaluation. The usage of large samples (more than 50 subjects) and when possible a control group, and advanced statistics are advised.

5. Conclusion

Since most of arm and forearm abnormalities may lead to altered muscle activity, compromised bones, joints and nerve integrity and affect local blood circulation, an uncommon temperature distribution pattern of the extremities surface may be observable through IRT (Berz and Sauer, 2007; Szentkuti et al., 2011).

IRT is a 100% safe, fast, easy to use and repeatable method that allows assessment of the effects that the surgical procedures, infections and inflammations treatments have on skin temperature. Moreover, it is a high sensible technique that detects temperature changes due to several pathologies, being, therefore, able to identify deviations from a healthy state. Hence, IRT has the potential to provide a physiologic profile study that may complement traditional medical exams in the arm and forearm health assessment (Berz and Sauer, 2007; Szentkuti et al., 2011).

Moreover, if further studies and challenges are addressed, the application of IRT in the arm and forearm health evaluation might progress and become a viable tool in the improvement of diagnosis, treatment and rehabilitation outcomes of the upper limbs.

Conflicts of interest

None.

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