Does the technique employed for skin temperature assessment alter outcomes? A Systematic Review

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1 Introduction

Skin temperature (T_{sk}) is an important physiological measure that can reflect the presence of illness and injury as well as provide insight into the localised interactions between the body and the environment. T_{sk} has a wide range of applications that consist of, but are not limited to, the assessment of: complex regional pain syndrome (Koban *et al.*, 2003; Wasner *et al.*, 2002), diabetic ulceration (Armstrong *et al.*, 1997), overuse injuries (Meknas *et al.*, 2008; Hildebrandt *et al.*, 2010), physiological strain (Cuddy *et al.*, 2013), hypoxia (Cipriano and Goldman, 1975), exercise performance (Kenefick *et al.*, 2010; Schlader *et al.*, 2011; Price, 2006), pacing strategies (Tucker, 2009), cold exposure (Bleakley *et al.*, 2012; Costello *et al.*, 2012a; Selfe *et al.*, 2006), fever screening (Bitar *et al.*, 2009; Chiu *et al.*, 2005; Nguyen *et al.*, 2010), thermal comfort and sensation (Wang *et al.*, 2007), circadian rhythm (Hasselberg *et al.*, 2013; van Marken Lichtenbelt *et al.*, 2006; Yosipovitch *et al.*, 1998), and when coupled with core body temperature, can determine mean body temperature (Colin *et al.*, 1971). Consequently, the assessment of T_{sk} is extremely important in clinical, occupational, sports medicine, exercise science and public health settings. The outline of this paper includes a critical review of the literature pertaining to human T_{sk} regulation, influences and a detailed exploration of measurement devices, leading to a subsequent systematic review of the agreement between infrared and conductive means of T_{sk} measurement.

The human body controls core body temperature within a tight band typically between 36 °C and 38 °C despite varying ambient temperatures. Thermoreceptors located within the hypothalamus, spinal cord, skin and some abdominal organs monitor temperature changes, and work via negative feedback to initiate autonomic mechanisms to either conserve (via shivering and vasoconstriction) or lose (via sweating and vasodilation) body heat (Casa *et al.*, 2007). For example, when core temperature rises during exercise, the anterior hypothalamus detects the temperature of blood perfusing it and once temperatures exceed an internal set point, vasodilation of peripheral blood vessels and sweat production facilitates heat loss (Charkoudian, 2003). Conversely, when core temperature is reduced, heat conservation mechanisms such as vasoconstriction of peripheral blood vessels and autonomic muscle tremors (i.e. shivering thermogenesis) limit heat loss from the skin into the environment (Van Someren *et al.*, 2002). As a result, T_{sk} is influenced by a number of factors including superficial blood flow, heat conduction from deeper tissues (including muscle) and heat loss along the skin's surface. The skin is also the site of reciprocal heat transfer between the human body and the external environment. The extent to which heat transfer occurs is largely dependent on the environmental conditions, such as ambient temperature, water vapour and the thermal properties of human skin (Prek and Butala, 2010).

The most common methods of assessing T_{sk} are derived from conductive and infrared devices. These techniques measure temperature by applying different scientific principles of thermal heat transfer. Conductive devices are based upon the transfer of heat energy into the device through direct contact with the object of interest. At a molecular level, conduction refers to the transfer of heat energy that occurs in all substances (i.e., solid, liquid and gas) between hot, rapidly moving or vibrating molecules (Lyklema, 2001). These faster (hotter) moving molecules transfer some heat energy to colder neighbouring particles when they collide. In the case of human heat transfer, conduction refers to the direct contact between the body, typically the skin, and another surface. Heat is transferred from the warmer body, proportionate to the size of the temperature gradient, surface area of contact, pressure between the two bodies and specific conductivity of the surfaces (Hardy *et al.*, 1938). There are a wide variety of types, makes and models of commercially available conductive devices. For the purpose of this review three of the most popular types of devices will be introduced. Thermocouples, thermistors and telemetry sensors (such as iButtons) are typical contact measures of T_{sk} that have been viewed as advantageous by clinicians due to the relatively low cost and the associated ease of use (Tyler, 2011). Thermocouples function as a result of an interaction known as the Seebeck effect; where by the temperature measured is proportional to the voltage between two dissimilar metals when in the presence of a temperature gradient (Klopfenstein, 1994). Thermocouples are advantageous due to their fast response and accuracy over very wide temperature ranges (Yadav *et al.*, 2012). Thermistors are a wired sensor made from a semi-conductive metal that exhibits an inverse relationship between temperature and the electrical resistance within the device. Thermistors exhibit high thermal sensitivity, fast response rates and are very accurate when measuring temperatures within the human physiological range (Klopfenstein, 1994). In order to function, both thermocouples and thermistors require an associated data logger to control sampling rates and store recorded data. Wireless thermochron sensors, provide an alternative to more cumbersome wired counterparts as an autonomous encapsulated semiconductor computer chip that performs similar to a thermistor sensor that has been validated against thermocouples (van Marken Lichtenbelt *et al.*, 2006) and thermistors (Harper Smith *et al.*, 2010).

Typically, infrared devices are used as a non-contact form of T_{sk} measurement and consist of infrared thermometers and infrared thermal imaging cameras. All objects hotter than absolute zero, produce an electromagnetic wave of radiation proportional to the electrical charge given off by vibrating atoms and molecules that make up the object. Emissivity (ε) is the term used to describe the amount of absolute radiation energy released from an objects surface relative to an ideal black body (ε = 1.0) while objects with an ε = < 1.0 are referred to as a grey body (Bernard *et al.*, 2013). The Stefan-Boltzmann law states that the power emitted per unit area of the surface of a black body is directly proportional to the fourth power of its absolute temperature:

$$E = \varepsilon \cdot \sigma \cdot T^4$$

where E is total emissive power ($W \cdot m^{-2}$), ε is the emissivity of the object, σ represents the Stefan-Boltzmann Constant (5.67×10^{-8} $W \cdot m^{-2} K^4$) and T the absolute temperature (K). By knowing the emissivity coefficient of an object’s surface it is possible to know the surface temperature of that object (Modest, 2013). Human skin, irrespective of ethnicity, has an emissivity resembling that of a perfect black body of approximately 0.98 (Boylan *et al.*, 1992; Steketee, 1973).

Similar to conductive devices, infrared thermometers measure the average temperature over a small area, often referred to as a ‘spot’ measurement. There are infrared thermometers that require contact with the area of measurement (i.e., skin); however, the majority of infrared devices are held off the skin which allows for temperature measurements without any physical contact. An internal detector collects the infrared energy of an object with a relatively simple ‘point and shoot’ design with an associated laser sighting for aiming purposes. Most clinically used devices have manufacturer specified distances, in which the device should be held from the skin to ensure accurate measurement (e.g., 50 mm).

However, some other thermometers use a distance to spot ratio that allows for a greater measurement area at longer distances though at the cost of accuracy (Thomas, 2006). Infrared cameras are characterised into two categories: cooled and uncooled. Cooled cameras require liquid nitrogen cooling and produce more accurate and sensitive measurements (Qi and Diakides, 2007). These cameras cost well outside the budgets of typical research laboratories (upwards of $30,000 USD) and are used almost exclusively in military engineering and commercial industries. Uncooled cameras used predominantly in medical settings are compact, portable and markedly cheaper than cooled cameras (Diakides, 1997); but the initial and associated costs make them a relativity expensive T_{sk} measurement device compared to cheaper conductive and infrared thermometer options. The use of an uncooled infrared camera typically requires the camera, a tripod and a connected computer for image display and image processing via dedicated software, although handheld devices have been developed. Modern uncooled cameras exhibit an erroneous thermal drift when turned on or moved (Ring *et al.*, 2007) and therefore, along with infrared thermometers, require at least 30 to 60 minutes to stabilise to the surrounding ambient conditions for accurate measurement (Grgić and Pušnik, 2011).

Extensive investigations regarding the validity of various techniques of core temperature measurement have taken place (Binkley *et al.*, 2002; Casa *et al.*, 2007; Ganio *et al.*, 2009; Taylor *et al.*, 2014). Conversely, despite the obvious differences in T_{sk} measurement techniques, and indeed the heat transfer principles used to assess T_{sk}, few authors have considered or compared the potential difference between conductive and infrared technologies. T_{sk} assessment methods have been largely investigated in isolation (i.e. conductive vs. conductive) with currently no recognised gold-standard criterion (Harper Smith *et al.*, 2010). Furthermore, over the past decade considerable advances in the technology leading to greater accuracy, functionality and affordability have seen infrared devices, particularly thermal imaging, become more widely adopted (Costello *et al.*, 2012b; Costello *et al.*, 2013). Investigations of conductive and infrared devices in isolation have shown differences in cost (Foto *et al.*, 2007; Harper Smith *et al.*, 2010), error (Bernard *et al.*, 2013; Harper Smith *et al.*, 2010; Psikuta *et al.*, 2013), response time (Foto *et al.*, 2007; Harper Smith *et al.*, 2010; van Marken Lichtenbelt *et al.*, 2006) and reliability (Hasselberg *et al.*, 2013; Long *et al.*, 2010; Zaproudina *et al.*, 2008). However, a paucity of research exists within the literature comparing measurement differences between conductive and infrared techniques.

Despite the differences in scientific principles underpinning each method, many scientists and practitioners assume interchangeability between devices under all circumstances. Current practice suggests that for any other device to be considered interchangeable localised T_{sk} differences should not exceed the proposed clinically significant mean difference (MD) of ± 0.5 °C and limits of agreement (LoA) of ± 1.0 °C (Bach *et al.*, 2015; James *et al.*, 2014; Joly and Weil, 1969; Kelechi *et al.*, 2011; Kelechi *et al.*, 2006; Maniar *et al.*, 2015; Marins *et al.*, 2014; Selfe *et al.*, 2008). Importantly, these relatively low thresholds illustrate that only small variations between devices are needed to produce erroneous data that significantly influences the conclusions drawn by scientists and practitioners. Due to the significant role of T_{sk} in thermoregulation and pathophysiology, a systematic review examining the validity of using conductive and infrared devices interchangeably is required. Therefore, our aim was to review the agreement between conductive and infrared means of assessing T_{sk} which are commonly employed throughout medicine, occupational health and safety, exercise science, public health and research settings.

2 Methods

2.1 Data Sources

Searches were performed in the Cochrane Central Register of Controlled Trials, MEDLINE, SportsDiscus, EMBASE and CINHAL. A total of 21 MeSH or keywords and their combinations were searched using Boolean operators (skin temperature, tissue temperature, surface temperature, valid*, reliab*, repeatability, interchange*, agreement, compar*, contrast, differences, contact, non-contact, ibutton*, thermograph*, thermistors, thermocouples, thermometer, radiom*, infrared camera, thermal imag*). Due to the advent of digital technology and substantial technological advances in the last 20 years, databases were adjusted to search for original papers published between January 1995 and January 2015. Potentially relevant articles were also obtained by physically searching the bibliographies of included studies to identify any study that may have escaped the original search. A total of 8,602 articles were identified for screening and review in accordance with the PRISMA format (Figure 1).

Figure 1 PRISMA flow chart describing the selection and exclusion of articles.

2.2 Study Selection

Two authors independently selected articles for inclusion. Following the search strategy titles and abstracts were screened for relevance. All relevant trials were flagged for full-text screening before a consensus between the two authors was reached. Where appropriate, we sought clarification by contacting primary authors regarding any methodological queries. Any disagreement for inclusion of a paper was resolved by a third party. Studies were retained provided the following criteria were not violated: 1) the literature was written in English, 2) participants were human (in vivo), 3) skin surface temperature was assessed at the same site, 4) with at least two commercially available devices employed – one conductive and one infrared – and 5) T_{sk} data was reported in the study.

2.3 Data Extraction

Data were extracted independently by two review authors using a customised form. This was used to extract relevant data on methodological design, participants, comparisons of devices (conductive and infrared) and techniques used, region of interest and environmental conditions. Any disagreement was resolved by consensus, or third-party adjudication. Where numerical values were not reported, data was manually extracted from any relevant graphs or figures. There was no blinding to study author, institution or journal at this stage.

2.4 Study heterogeneity

Meta-analyses were not undertaken because of heterogeneity in the included studies. This related to diversity in terms of a number of key study characteristics: devices used, ambient conditions, activity (e.g. exercise/rest), and body part assessed. Individual effect sizes were calculated and presented on forest plots (MD, 95% confidence intervals [95% CI]) to provide a graphic overview of the results (Figure 2).

Figure 2 Forest plot T_{sk} comparison for all possible included studies (10 of 16): Conductive vs. Infrared, outcome: T_{sk} mean difference (MD) ± standard deviation (SD) based upon number of observations (Total) and 95% confidence intervals (95% CI). TM = Thermistor; IT = Infrared thermometer; TN = Thermochron; IC = Infrared camera; IT1 = 3000A (Genius, Sherwood IMS, California, USA); IT2 = DT-1001 (Exergen, Massachusetts, USA); C4 = Cervical vertebrae 4; L4 = Lumbar vertebrae 4.

2.5 Risk of Bias

For all included studies, methodological quality was assessed by two authors independently, using the Cochrane risk-of bias tool (Figure 3). Each study was graded for the following domains; random sequence generation (selection bias), blinding (assessor bias), incomplete outcome data (attrition bias), selective reporting (reporting bias) and other sources of bias (e.g. no device calibration, failure to control for influencing factors). For each study, the domains were described as reported in the published study report (or if appropriate based on information from related protocols, published comments or through personal correspondence with the original investigators) and judged by the review authors as to their risk of bias. They were assigned 'low' if criteria for a low risk of bias are met or 'high' if criteria for a high risk of bias are met. If insufficient detail of what happened in the study was reported, or if what happened in the study was known, but the risk of bias was unknown, then the risk of bias was deemed 'unclear' for that domain. Disagreements between authors regarding the risk of bias for domains were resolved by third part evaluation.

Figure 3 Included Studies: Cochrane risk of bias summary

3 Results

3.1 Study Description

Sixteen articles met the inclusion criteria for this review, the characteristics of which are summarised in Table 1. One article was excluded from the current review as the data were previously reported in a subsequent publication (Roy *et al.*, 2006a). This was confirmed following personal communication with the authors. Of the sixteen studies the total sample comprised of 245 adult (140 male, 67 female) and 15 infant participants (8 male, 2 female); the gender of 38 adults (Ruopsa *et al.*, 2009) and 5 infants (Karlsson *et al.*, 1995) was unknown. The mean sample of the pooled studies was 16, with a range of 3 (Korukçu and Kilic, 2009) to 55 participants (Kelechi *et al.*, 2006). Participant mean ages ranged from 2-7 days old (Karlsson *et al.*, 1995) to 70 years (Kelechi *et al.*, 2006); three studies failed to report the age of the participants (Chuang *et al.*, 1997; Johnstone *et al.*, 2012; Ruopsa *et al.*, 2009). Fifteen of the sixteen investigations used an observational study design, with one randomised crossover trial (Fernandes *et al.*, 2014). In relation to statistical power three studies (Bach *et al.*, 2015; James *et al.*, 2014; Kelechi *et al.*, 2006) incorporated a prospective power analysis to identify the sample size necessary to achieve statistical significance.

3.2 Results of Individual Studies

All available data, MD; 95% CI and MD; LoA, is presented in Figure 3 and Table 1 respectively. Of the sixteen included studies comparing conductive and infrared methods of assessing T_{sk}, five types of devices were used; thermistors, thermocouples, telemetry sensors, infrared cameras and handheld infrared thermometers. Within the handheld infrared thermometers, both contact and non-contact models were utilised. In addition, two studies (Burnham *et al.*, 2006; Matsukawa *et al.*, 2000) used a tympanic infrared thermometer; one with a T_{sk} probe attached (Matsukawa *et al.*, 2000) while Burnham *et al.* (2006) used the tympanic device set to 'surface' measurement function while concurrently testing an additional infrared device specialised for human skin. Two studies (Bach *et al.*, 2015; Burnham *et al.*, 2006) tested the agreement of multiple infrared and/or conductive devices from a single sample. Detailed information pertaining to the individual devices is reported in Table 1. Local T_{sk} was measured at the face, shoulder, chest, back, paraspinal regions, forearm, hand and fingers, thigh, lower leg and foot. Four studies (Bach *et al.*, 2015; Buono *et al.*, 2007; Fernandes *et al.*, 2014; James *et al.*, 2014) compared mean skin temperature ($\bar{T}_{sk}$) values between devices using the 4-site (International

Organisation for Standardisation, 2004), 3-site (Burton, 1935), 8-site (Nadel *et al.*, 1973) and 4-site (Ramanathan, 1964) equations respectively. Measurements were taken with devices during rest (Bach *et al.*, 2015; Buono *et al.*, 2007; Chuang *et al.*, 1997; Fernandes *et al.*, 2014; Heimann *et al.*, 2013; James *et al.*, 2014; Karlsson *et al.*, 1995; Kelechi *et al.*, 2011; Kelechi *et al.*, 2006; Roy *et al.*, 2006b; van den Heuvel *et al.*, 2003), exercise (Buono *et al.*, 2007; Fernandes *et al.*, 2014; Johnstone *et al.*, 2012), passive heating (Karlsson *et al.*, 1995; Korukçu and Kilic, 2009; Matsukawa *et al.*, 2000), exercise in the heat (Bach *et al.*, 2015; James *et al.*, 2014; Johnstone *et al.*, 2012) and passive cooling (Buono *et al.*, 2007; Kelechi *et al.*, 2011; Korukçu and Kilic, 2009). It was not clear what environmental conditions were employed in two studies (Burnham *et al.*, 2006; Ruopsa *et al.*, 2009) but based on the information in the text it appears that these studies took place in stable air-conditioned environments with the participants passively resting. Reported ambient temperatures ranged from 15 °C (Buono *et al.*, 2007) to 38 °C (Bach *et al.*, 2015), with only four studies (Bach *et al.*, 2015; Buono *et al.*, 2007; Fernandes *et al.*, 2014; James *et al.*, 2014) reporting an average relative humidity; ranging from 40% (Buono *et al.*, 2007) to 62% (Fernandes *et al.*, 2014).

Table 1 Articles Included in the Systematic Review

Authors	Techniques			Sample Size (M:F); Age (y)^	Sites	Methods and Conditions	Findings
	Conductive	*Infrared*	*Calibrated*				
Bach et al. (2015)	TM[A] TN[C]	IT[B] IC[D]	Yes	30 (30:0) healthy; 25.0 ± 2.9	$\bar{T}_{sk}$ reported – 4 site formula[1] (Neck, Scapula, Hand, Shin)	1. Seated rest Acclimation: 20 min Duration: 30 min T_{room}: 24.0 ± 1.2 °C (56 ± 8% RH) Other: wind speed (ν <0.1 m·s^{-1}) 2. Cycle ergometry (120 W) T_{room}: 38.0 ± 0.5 °C (41 ± 2% RH) Duration: 30 min Other: wind speed (ν <0.5 ± 0.1 m·s^{-1}) 3.Seated recovery Duration: 45 min T_{room}: 24.0 ± 1.2 °C (56 ± 8% RH) Other: wind speed (ν <0.1 m·s^{-1})	1. Rest IT > TM; MD 0.34 °C (LoA -0.1 °C, -0.78 °C) IC > TM; MD 0.83 °C (LoA 0.06 °C, 1.6 °C) IT > TN; MD 0.33 °C (LoA 0.11, 0.55) ***** IC > TN; MD 0.82 °C (LoA 0.45 °C, 1.19 °C) * 2. Cycle IT < TM; MD -0.44 °C (LoA -1.67 °C, 0.79 °C) IT < TN; MD -0.71 °C (LoA -1.59 °C, 0.17 °C) ***** 3. Recovery IT > TM; MD 1.04 °C (LoA -0.71 °C, 2.79 °C) IC > TM; MD 1.88 °C (LoA 0.01 °C, 3.75 °C) IT > TN; MD 0.67 °C (LoA -0.41 °C, 1.75 °C) ***** IC > TN; MD 1.51 °C (LoA -0.04 °C, 3.06 °C) *
Buono et al. (2007)	TM[E]	IT[F]	Yes	6 (6:0) healthy; 25 ± 3	$\bar{T}_{sk}$ reported – 3 site formula[2] (Chest, Forearm, Calf)	1. Seated rest Acclimation: 10 min T_{room}: 15, 25, 35 °C (40% RH) Other: wind speed (ν <1.0 m·s^{-1}) 2. Treadmill (4.82 km·h^{-1}, 0% Grade) Duration: 15 min T_{room}: 15, 25, 35 °C (40% RH)	1. Rest 15°C: IT < TM; MD -0.2 °C (LoA = NR) # 25°C: IT > TM; MD 0.3 °C (LoA = NR) # 35°C: IT > TM; MD 0.9 °C (LoA = NR) # 2. Run 15°C: IT < TM; MD -0.1 °C (LoA = NR) # 25°C: IT < TM; MD -0.5 °C (LoA = NR) # 35°C: IT > TM; MD 0.1 °C (LoA = NR) #
Burnham et al. (2006)	TM[G]	1. IT[H] 2. IT[I]	Yes	17 (12:5) healthy; 29.5 ± 8.5	Shoulder Forearm Hand Thigh Shin Foot	Mode: NR Acclimation: NR T_{room}: NR	1. IT[**D**] vs. TM All Sites: IT < TM; MD -0.5 °C (LoA = NR) 2. IT[**E**] vs. TM All Sites: IT < TM; MD -0.2 °C (LoA = NR)
Chuang et al. (1997)	TM[J]	TC[K]	NR	12 (8:4); palmar hyperhidrosis; 13 – 29	Thumb/Thenar	Mode: During/after T2 sympathectomy Acclimation: NR T_{room}: 20 – 23 °C (% RH = NR)	Left Hand IC < TM; MD -0.1 °C # (LoA = NR) Right Hand IC < TM; MD -0.65 °C # (LoA = NR)
Fernandes et al. (2014)	TC[L]	IC[M]	NR	12 (12:0) healthy; 22.4 ±3.3	$\bar{T}_{sk}$ reported – 8 site formula[3] (Forehead, Chest, Abdomen Scapula, Arm, Forearm, Thigh Calf)	1. Seated rest Acclimation: 60 min Duration: 30 min 2. Treadmill (60% VO_{2max}) Duration: 15 min 3. Standing recovery Duration: 60 min T_{room} (TC): 24.9 ± 0.6 °C (62 ± 6% RH) T_{room} (IC): 24.8 ± 0.4 °C (62 ± 5% RH)	1. Rest 15th min IC > TC; MD 0.75 °C (LoA -0.03 °C, 1.53°C) 2. Run 30th min IC < TC; MD -1.22 °C (LoA -2.61 °C, 0.16 °C) 3. Recovery 30th min IC > TC; MD 1.16 °C (LoA -0.15 °C, 2.48 °C)
Heimann et al. (2013)	TM[N]	IC[O]	NR	10 (8:2) preterm infants; 36 days old (12-62 days)	Back Upper abdomen	Acclimation: NR T_{room}: 24 – 26 °C (% RH = NR)	Back: IC < TM; MD -0.31 °C (LoA = NR) ***** Abdomen: IC < TM; MD -0.33 °C (LoA = NR) *****

Table 1 Cont.

Authors	Techniques			Sample Size (M:F); Age (y)^	Sites	Methods and Conditions	Findings
	Conductive	*Infrared*	*Calibrated*				
James et al. (2014)	TC[P]	IC[Q]	Yes	14 (14:0) club runners; 38 ± 11	$\bar{T}_{sk}$ reported – 4 site formula[4] (Chest, Upper Arm, Thigh, Calf)	1. Seated rest Acclimation: 10 min Duration: 35 min T_{room}: 31.9 ± 1 °C (61 ± 8.9% RH) 2. Treadmill (5 stage incremental test) Duration: 20 min T_{room}: 31.9 ± 1 °C (61 ± 8.9% RH)	Rest 10th min: IC < TM; MD -0.75 °C (LoA -2.03 °C, 0.53 °C) Rest 20th min: IC < TM; MD -0.89 °C (LoA -1.94 °C, 0.16 °C) Rest 25th min: IC < TM; MD -1.04 °C (LoA -2.21 °C, 0.13 °C) Rest 30th min: IC < TM; MD -0.83 °C (LoA -1.84 °C, 0.18 °C) Rest 35th min: IC < TM; MD -0.85 °C (LoA -2.06 °C, 0.36 °C) Exercise 4th min: IC < TM; MD -2.12 °C (LoA -4.34 °C, 0.10 °C) Exercise 8th min: IC < TM; MD -1.82 °C (LoA -2.92 °C, -0.72°C) Exercise 12th min: IC < TM; MD -1.93 °C (LoA -3.20 °C, -0.66°C) Exercise 16th min: IC < TM; MD -1.86 °C (LoA -3.14 °C, -0.58°C) Exercise 20th min: IC < TM; MD -1.94 °C (LoA -3.38 °C, -0.50°C)
Johnstone et al. (2012)	TM[R]	IT[S]	NR	10 (10:0) healthy active; NR	Chest	1. Sub-maximal cycle ergometry (60 rpm^{-1}, 4% body mass) Duration: 45 min T_{room}: 20.0 ± 0.1 °C (% RH = NR) 2. Sub-maximal cycle ergometry (60 rpm^{-1}, 4% body mass) Duration: 45 min T_{room}: 30.0 ± 0.1 °C (% RH = NR)	1. Cycle (20 °C) IT > TM; MD 0.03 °C (LoA -0.09 °C, 0.15°C) 2. Cycle (30 °C) IT < TM; MD -0.49 °C (LoA -1.85 °C, 0.87°C)
Karlsson et al. (1995)	TM[T]	IC[U]	Yes	5 (NR) full term healthy infants; 2-7 days old	NR; (IC adjacent to TM)	T_{room}: 29 – 32 °C (% RH = NR)	IC > TM; MD = NR, but stated within 0.5 °C (LoA = NR)
Kelechi et al. (2011)	TM[V]	IT[W]	NR	17 (2:15) healthy; 29.5 ± 8.5	Medial aspect of lower right leg	Lying rest Acclimation: 10 min T_{room}: 23 ± 1.3 °C (% RH = NR) Other: 1. post 10 min acclimation 2. further 10 min 3. after 10 min cold application	1. IT > TM; MD 0.2 °C (LoA -0.78 °C, 1.18 °C) ***** 2. IT > TM; MD 0.1 °C (LoA -0.70°C, 0.90 °C) ***** 3. IT > TM; MD 0.3 °C (LoA -2.50 °C, 3.10 °C) *****
Kelechi et al. (2006)	TM[V]	IT[X]	Yes	55 (26:29); 69.8 ± 11.5	Medial aspect of lower legs	Seated rest Acclimation: 10 min T_{room}: 22 °C (% RH = NR) Other: Assessed on 3 days	Day 1. Left Leg: IT < TM; MD -0.13 °C (LoA -1.45 °C, 1.72 °C) Day 1. Right Leg: IT < TM; MD 0.10 °C (LoA -1.32 °C, 1.11 °C) Day 2. Left Leg: IT < TM; MD -0.16 °C (LoA -1.11 °C, 1.43 °C) Day 2. Right Leg: IT < TM; MD 0.09 °C (LoA -1.31 °C, 1.14 °C) Day 3. Left Leg: IT = TM; MD 0.00 °C (LoA -1.43°C, 1.44 °C) Day 3. Right Leg: IT < TM; MD 0.21 °C (LoA -1.56 °C, 1.13°C)
Korukcu and Kilic (2009)	TC[Y]	IC[Z]	NR	3 (3:0) healthy; 25 ± 2.6	Face Forearm Finger	1. Passive heating 2. Passive cooling Duration: 30 min (each) T_{room}: NR	1. IC < TC; MR = NR (LoA = NR) 2. IC > TC MR = NR (LoA = NR) Stated that maximum differences between IC and TC < 2 °C at any instance during heating or cooling period.
Matasukawa et al. (2000)	TC[A1]	IT[A2]	NR	10 (10:0) healthy; 30 ± 5	Forearm Finger	Recovery from local passive heating Duration: 30 min T_{room}: 22 – 23 °C (% RH = NR)	Forearm: IT < TC; MD -0.5°C (LOA -1.48 °C, 0.48 °C) Finger: IT < TC; MD -0.5°C (LOA -1.48 °C, 0.48 °C)

Table 1 Cont.

Authors	Techniques			Sample Size (M:F); Age (y)^	Sites	Methods and Conditions	Findings
	Conductive	*Infrared*	*Calibrated*				
Roy et al. (2006)	TM[A3]	IT[A4]	NR	17 (6:11) healthy; 25.6 ± 5.4	Paraspinal (C4 & L4)	Prone rest Acclimation: 20 – 30 min T_{room}: 20.5 – 23.3 °C (% RH = NR) Other: Assess on 4 days	Overall: Left L4: IT > TM; MD 1.56 °C (LoA 0.44 °C, 2.61 °C) Right L4: IT > TM; MD 1.62 °C (LoA 0.05 °C, 3.16 °C) Left C4: IT > TM; MD 1.23 °C (LoA -0.44 °C, 2.88 °C) Right C4: IT > TM; MD 1.67 °C (LoA -0.22 °C, 3.55 °C)
Ruopsa et al. (2009)	TC[A5]	IT[A6]	Yes	38 (NR); NR	Middle finger both hands	Acclimation: NR T_{room}: NR	T_{sk} between 31.5 – 35 °C: IT < TC; MD -0.06 °C (LoA = NR) T_{sk} between 21.5 – 31.4 °C: IT < TC; MD -1.01 °C(LoA = NR)
van den Heuvel et al. (2003)	TM[A7]	IC[A8]	Yes	4 (1:3) healthy; 26.8 ± 2.2	Fingertips Palms Forearms Feet	Seated or supine rest Acclimation: 15 min T_{room}: 25 ± 1 °C (% RH = NR)	All Sites: IC < TM; MD -2.32°C (LoA -2.12 °C, -2.52 °C)

TM = Thermistors, **TC** = Thermocouples, **TN** = Thermochron, **IT** = Handheld Infrared Thermometer, **IC** = Infrared Camera, **M** = Male, **F** = Female, **W** = Watts, **°C** = Degrees Celsius, T_{sk} = Skin Temperature, $\bar{T}_{sk}$ = Mean Skin Temperature, T_{room} = Room Temperature, **RH** = Relative Humidity, **NR** = Not Reported, **MD** = Mean Difference, **LoA** = Limits of Agreement. ^ = Data for ages are presented in whole y, means ± SD or not reported where stated. * = Received through first author correspondence. [#] = Derived from graphs presented in publication. [A] = EU-UU-VL5-0 (Grant Instruments, UK), [B] = Visiofocus 06400 (Tecnimed, Italy), [C] = DSL922L-F50 (Maxmim Integrated, USA), [D] = A305sc (FLIR Systems, USA); [E] = Series 400 (YSI, USA), [F] = (Extech Instruments, USA); [G] = 113050 (Rochester Inc., USA), [H] = 3000A (Sherwood IMS Inc., USA), [I] = DT-1001 (Exergen, USA); [J] = Themo Tracer TH 1106/I-B (NEC San-Ei Instruments Ltd. Japan), [K] = M1029A (Hewlett Packard, USA); [L] = S-09K (Instrutherm, Brazil), [M] = ThermaCam T420 (FLIR Systems, USA); [N] = NR, [O] = VarioCam hr-Head (InfraTech GmbH, Germany); [P] = EUS-U-VS5-0 (Eltek, UK), [Q] = e40BX (FLIR Systems, USA); [R] = EUS-U-V5-V2 (Grant Instruments, UK), [S] = Bioharness (Zephyr, USA); [T] = Craft temperature sensor (Astra Tech, Sweden), [U] = Thermovision 750M (AGEMA Infrared Systems, Sweden); [V] = PeriFlux 5020 Temperature Unit (Perimed, Sweden), [W] = TempTouch (Diabetica Solutions, USA); [X] = ThermoTrace Model 15012 (DeltaTrak, USA ; [Y] = T-type thermocouples (Physitemp, USA), [Z] = ThermaCam SC640 (FLIR Systems, USA); [A1] = Mon-a-Therm (Mallinckrodt Anaesthesiology Products, USA), [A2] = Tympanic IT with attached T_{sk} probe (Genius, USA); , [A3] = Model Et-016-STP/OWL-ET-016-STP (General Electric via Digi-Key, USA), [A4] = Subluxation Station Insight 7000 (EMG Consultant Inc., USA); [A5] = (Datex-Engstom, Finaland), [A6] = PhotoTemp MX6 (Raytek, USA): [A7] = Steri-Probe type 499B (Cincinnati Sub Zero, USA), [A8] = MMS Med2000 camera (Meditherm, Australia). [1] International Organisation for Standardisation 2004 ISO 9886: Ergonomics - Evaluation of thermal strain by physiological measurements. (Geneva, Switzerland: International Organization for Standardization); [2] Burton A C 1934 A new technique for the measurement of average skin temperature over surfaces of the body and changes in skin temperature during exercise *The Journal of Nutrition* **7** 481-96; [3] Nadel E, Mitchell J and Stolwijk J 1973 Differential thermal sensitivity in the human skin *Pflügers Archiv* **340** 71-6; [4] Ramanathan, N L 1964 A new weighting system for mean surface temperature of the human body *Journal of Applied Physiology* **19** 531-33.

4 Discussion

4.1 Evaluation of Methodological Quality

There were large limitations within the current evidence base. Sample size was consistently small and the subsequent power of individual trials was questionable. The number of participants in each of the included studies was generally small, with only three of the included studies (Bach *et al.*, 2015; Kelechi *et al.*, 2006; Ruopsa *et al.*, 2009) using a sample greater than 17 participants. The majority of studies failed to report a priori power analysis, potentially preventing robust conclusions to be drawn from the evidence. There was also a consistently unclear or high risk of bias across the studies, in terms of random sequence generation, incomplete outcome data,selective reporting and other sources of bias (e.g. no device calibration, failure to control for all influencing factors).

4.2 Summary of Findings

This systematic review sought to identify any measurement discrepancies between conductive and infrared T_{sk} measurement. Any clinically significant differences between devices would inform practitioners regarding the use, or validation, of these devices in clinical or research settings. Overall, twelve studies found clinically significant differences with either MD's greater than ± 0.5 °C and/or LoA greater than ± 1.0 °C between T_{sk} measurements (Bach *et al.*, 2015; Buono *et al.*, 2007; Burnham *et al.*, 2006; Chuang *et al.*, 1997; James *et al.*, 2014; Johnstone *et al.*, 2012; Kelechi *et al.*, 2011; Kelechi *et al.*, 2006; Matsukawa *et al.*, 2000; Roy *et al.*, 2006b; Ruopsa *et al.*, 2009; van den Heuvel *et al.*, 2003). One study reported overall differences less than 0.5 °C (LoA < ± 1.0 °C), two studies did not specifically report MD between devices (Karlsson *et al.*, 1995; Korukçu and Kilic, 2009) and the remaining study did not report LoA, however had MD less than ± 0.5 °C (Heimann *et al.*, 2013). Moreover, six of the studies reported MD's in excess of 1.0 °C (Bach *et al.*, 2015; Fernandes *et al.*, 2014; James *et al.*, 2014; Roy *et al.*, 2006b; Ruopsa *et al.*, 2009; van den Heuvel *et al.*, 2003). Based upon the collective findings we advise that insufficient agreement exists between infrared and conductive measurement T_{sk} devices irrespective of the ambient conditions. However, due to limited quality of the available evidence the subsequent discussion will aim to interpret the collected literature to better understand device limitations and potential mechanisms for differences between infrared and conductive T_{sk} devices.

4.3 Resting Thermoneutral Conditions

Eleven studies were undertaken during rest in air-conditioned environments making it the most predominant testing condition of the included studies. As a whole, there seemed to be no consistent trend for one type of device to overestimate against the other. Six reported that conductive devices tended to measure higher T_{sk} than infrared (Burnham *et al.*, 2006; James *et al.*, 2014; Kelechi *et al.*, 2006; Matsukawa *et al.*, 2000; Ruopsa *et al.*, 2009; van den Heuvel *et al.*, 2003), while the other five reported infrared instruments tended to measure higher than conductive (Bach *et al.*, 2015; Buono *et al.*, 2007; Fernandes *et al.*, 2014; Kelechi *et al.*, 2011; Roy *et al.*, 2006b). Infrared thermometers were more commonly investigated than infrared cameras, with eight and four studies implementing each device respectively. The current evidence suggests that infrared thermometers are within clinically acceptable agreement (within ± 0.5 °C MD, ± 1.0 LoA) in five of the eight studies. One of the studies however, showed that infrared measurements taken of the fingers on both the left and right hands were in agreement and only marginally underestimating by 0.06 °C between finger temperatures of 31.5 °C and 35 °C (Ruopsa *et al.*, 2009). Significantly greater underestimation of 1.01 °C was seen with finger temperatures between 21.5 °C and 31.4 °C. The authors provided no reasons as the why these differences occurred, although it was stated that "*The lowest temperatures were recorded from volunteers who had just arrived indoors following exposure to cold winter weather, and their fingers had not yet warmed up*" (Ruopsa *et al.*, 2009). Therefore, it is reasonable to conclude that the infrared thermometer significantly underestimated T_{sk} due to the absence of an adequate stabilisation period. Placing a taped thermocouple over a finger would create an insulating effect raising the T_{sk} immediately under the probe faster than the colder, exposed part of the finger. The central theme from the applicable studies was the reported the agreement between calibrated infrared cameras and conductive devices. Even while under laboratory controlled, resting conditions, all four studies found differences exceeding clinical significance, ranging from to -2.32 °C (LoA -2.12 °C, -2.52 °C) (van den Heuvel *et al.*, 2003) to 0.83 °C (LoA 0.06 °C, 1.60 °C). With each of the authors questioning the accuracy of the respective infrared camera compared to a traditional conductive counterpart. These findings have implications for clinical, public health and research applications where agreement of infrared cameras may be assumed.

4.4 Metabolic and Environmental Heating

Based on the current evidence there appeared to be no systematic over or underestimation of infrared devices under stable resting conditions. However, regardless of the direction of differences (over or underestimation) by infrared means, the introduction of stressors such as environmental heat or the commencement of exercise saw marked increases in MD compared to stable resting conditions (Bach *et al.*, 2015; Buono *et al.*, 2007; Fernandes *et al.*, 2014; James *et al.*, 2014; Johnstone *et al.*, 2012). Interestingly, in the five studies that recorded measurements at rest in an air-conditioned environment, the application of an external stressor (i.e., exercise and/or heat) saw MD augmented in all studies and by as much as an additional 1.08 °C (James et al., 2014). In a comprehensive investigation of the reliability and validity of T_{sk} devices, James *et al.* (2014) found significant MD of -2.12 °C (LoA -4.34 °C, 0.10 °C), between thermocouples and a calibrated infrared camera during exercise in the heat. The authors concluded that infrared cameras were not appropriate for T_{sk} assessment during exercise. The most recent evidence presents analogous evidence of unacceptable agreement between infrared devices and thermistors (Bach *et al.*, 2015), thermocouples (Fernandes *et al.*, 2014; James *et al.*, 2014) or telemetry sensors (Bach *et al.*, 2015). These results are most likely a product of sweat developing on the skins surface changing the emissivity of the skin causing the infrared device to underestimate T_{sk} compared to the conductive comparison (Bernard *et al.*, 2013). It should be noted that none of the included studies attempted to measure localised sweat rates at the measurement sites.

Fernandes *et al.* (2014) measured T_{sk} at rest, exercise and recovery through a randomised crossover design to compare thermocouples and an infrared camera on separate days. The ability to make accurate comparisons between the two devices was dependent on the homogeneity of baseline and responses of T_{sk} in the same person between the two testing days. The authors attempted to control for the natural 24 hour circadian variation in T_{sk}, by conducting testing at the same time of day and randomising device allocation. However, day-to-day variations in skin blood flow (Sundberg, 1984) and T_{sk} (Sarabia *et al.*, 2008) have previously been reported in healthy participants even when time of day is controlled for. Therefore, it is possible that these differences may have been affected by the methodological design of the study. Nevertheless, differences of -1.22 °C (LoA -2.61 °C, 0.16 °C) are comparable to similar investigations that suggest differences using infrared and conductive devices simultaneously are a due to a confounding factor (most likely sweat) as a result of the commencement (Bach *et al.*, 2015; Buono *et al.*, 2007; Fernandes *et al.*, 2014; James *et al.*, 2014; Johnstone *et al.*, 2012) and cessation (Bach *et al.*, 2015; Fernandes *et al.*, 2014) of exercise and/or heat exposure. These results are particularly important in occupational, public health and sporting applications due to current absolute limits for fever diagnosis (Bitar *et al.*, 2009; Chiu *et al.*, 2005; Nguyen *et al.*, 2010) and of workplace standards for safe T_{sk} (International Organisation for Standardisation, 2004). Occupational settings that present high thermal loads run the risk of decreased productivity and employee safety. Therefore, the standardisation of safety limits for the maximum physiological temperatures of core and skin have been set to 39.5 °C and 43 °C respectively (International Organisation for Standardisation, 2004). Industries with the greatest risks of exposing workers to high thermal loads include manufacturing (Fogleman *et al.*, 2005), agriculture (Jackson and Rosenberg, 2010), mining (Hunt *et al.*, 2012), emergency services (Bourlai *et al.*, 2012), construction (Lundgren *et al.*, 2013) and participation in the armed forces (Carter III *et al.*, 2005). Further to this, studies observing manufacturing injury rates have reported a significantly greater number of injuries when workplace temperatures exceed 32 °C (Fogleman *et al.*, 2005). Therefore, it is imperative that absolute values of T_{sk} are accurately measured in occupational settings.

4.5 Cryotherapy and Environmental Cooling

Three studies (Buono *et al.*, 2007; Kelechi *et al.*, 2011; Korukçu and Kilic, 2009) compared devices under cold environmental conditions; more specifically, 10 °C ambient temperatures (Buono *et al.*, 2007), forced air cooling (Korukçu and Kilic, 2009) and following 10 minutes of ice pack application (Kelechi *et al.*, 2011). Buono *et al.* (2007) found no statistical or clinical differences between a thermistor and an infrared thermometer when determining $\bar{T}_{\text{sk}}$ during passive rest or exercise in cold ambient conditions, with MD of 0.2 °C and 0.1 °C respectively. Kelechi *et al.* (2011) used a glycerine-based gel wrap to cool the measurement site and reported 71% (12/17) of measurements taken between a thermistor and infrared thermometer were outside the clinically important MD (± 0.5 °C) with a MD of 0.3 °C (LoA -2.50 °C, 3.10 °C). However, this study did not control the application of the cold gel which was placed directly over the thermistor probe at different pressures and locations over the measurement site. Consequently, these findings should be treated with caution. Finally, Korukçu and Kilic (2009) used a thermocouple to validate the use of an infrared camera during passive cooling in an automobile, recording every 10 s for 30 min. On average the thermocouple recorded greater T_{sk} values than that of the infrared camera, but unfortunately the MD and LoA between the devices was not reported. However, it was noted that differences did not exceed 2 °C at any time. This quality of evidence leaves little understanding of the influence to which cryotherapy or localised cooling interventions potentially exacerbate differences between devices, with small sample sizes and limited comparisons between instruments under these acute settings.

4.6 Pathophysiology and Disease

Although comprehensive in data collection, temperature representation, non-contact benefits for injured or infectious patients and wide range of use across the medical community, infrared thermography has little evidence to support the adequate agreement with conductive devices in human applications. In some cases the relative temperature change in medical scenarios is the more important measure than an absolute such as temperature change over time to monitor diabetic ulceration (Armstrong *et al.*, 1997). However, recent research suggest it should not be assumed that relative T_{sk} oscillations will be analogous between infrared and conductive devices under all circumstances (Bach *et al.*, 2015). Only one study met the inclusion criteria for this systematic review utilised participants with skin pathology (palmar hyperhidrosis). Chuang *et al.* (1997) observed underestimation of Tsk via infrared camera compared to thermistors and differences between the left and right hands were not uniform, 0.1 and 0.65 respectively. Speculatively, this may indicate that the progression of the pathology at a local site itself could cause measurement error. The tendency for infrared devices to measure lower T_{sk} is supported by a recent review of temperature measurements at several sites around the knee in over 2900 participants (Ammer, 2012). The included studies in the review by Ammer (2012) utilised a single measurement technique and when pooled with comparable studies, it was noted on average that regardless of healthy or arthritic knees, contact thermometers measured higher knee temperatures than that of infrared thermography. It is important to note that differences between contact and non-contact devices tended to be greater in arthritic knees than healthy equivalents, 2 °C and 1 °C respectively.

4.7 Neonates

Preterm Neonates have low levels of fat, thin skin, and high evaporative losses consequently leading to body temperature directly influencing the morbidity and mortality (Hammarlund and Sedin, 1979). Monitoring of both skin and rectal measurements are imperative to successful preterm infant health outcomes (Van Der Spek *et al.*, 2009). Only two studies identified in the current review investigated T_{sk} measurement differences in preterm (Heimann *et al.*, 2013) and full term (Karlsson *et al.*, 1995) infants. Overall, each study found small differences that were less than the clinically significant limits of ± 0.5 °C leading all authors to support the use of infrared cameras for infants temperature monitoring.

4.8 Sources of Error

Currently, very few studies pooled in this review comprehensively accounted for the environmental, individual or technical factors that are potentially the source of erroneous measurements from infrared thermography (Fernández-Cuevas *et al.*, 2015). Controlled infrared device set up including accurate measurement position, distance and recorded and stabilised environmental conditions can determine the quality of data collected. Camera distance should vary upon the size of the measurement area and the optical specifications of the camera. To maximise data collection by increasing functional pixels, an infrared camera should be placed as close as possible so the measurement surface fills the entire field of view while maintaining focus (Ammer, 2003). For the most accurate temperature measurements infrared devices are required to be positioned perpendicular to the measurement surface of interest. Any deviation away from 0° causes the device to read thermal radiation from the surroundings being reflected from the skin (Watmough *et al.*, 1970). Ammer (2003) reported deviations between 0 and 30° alter the emissivity values of the skin and begin to limit the radiative energy measured by the device, while deviations of 30° and 60° produce substantially erroneous data (± 1 °C). In order to minimise any environmental influences, data collection should be conducted in a stable controlled setting between 18 and 25 °C (Ring and Ammer, 2000), free of external radiation sources (i.e., sun) and the use of a uniform matte background behind the participant is recommended to avoid any reflective radiation (Costello *et al.*, 2012b). Furthermore, the presences of ointments, cosmetics, liquids and hair on the measurement area can cause inaccurate infrared readings (Bernard *et al.*, 2013; Korichi *et al.*, 2006; Steketee, 1976). Human hair is an avascular structure with a lower emissivity, thermal conductivity and heat capacity than human skin and has been shown to produce relatively lower temperatures than hair-free skin (Togawa and Saito, 1994). Therefore, in the presence of body hair shaving should take place in the days preceding testing to avoid razor micro-trauma artificially raising T_{sk} (Merla *et al.*, 2010). The topical application of water, creams and gels has been shown to produce reductions in T_{sk} measurements through infrared means by up to 4.86 °C (Bernard *et al.*, 2013). Overall, each of these substances mentioned creates a physical barrier, with unique emissive and thermal properties, between the skin surface and the infrared detector. Therefore, it should be recommended that before infrared T_{sk} measurements, participants should have any relevant regions of interest cleaned with alcohol (allowed to dry) and be free of hair. Unfortunately, very few investigations adhered to many of these recommendations or failed to report sufficient methodological controls. This cumulative effect of uncontrolled influencing factors on infrared measurements could explain conflicting results reported between studies.

Due to methodological constraints of conductive devices, potential errors have been proposed as a result of conductive and infrared devices simultaneously measuring adjacent and not identical measurement sites and natural T_{sk} variation within a given region of interest. Skin blood flow variations as result of compensatory mechanisms to thermal stress (hot or cold) could also explain differences between adjacent devices measuring within a region of interest. Under cold ambient temperatures sympathetic stimulation prompts vasoconstriction of blood vessels to direct blood supply away from the skin, reducing heat loss into the environment. A consequence of this mechanism is greater variation in T_{sk}

within a region of interest (Frim *et al.*, 1990). Conversely, under hot conditions an increase in blood flow to the skin sees a concomitant distribution of T_{sk} that is more uniform within a region of interest (Webb, 1992). However, a recent investigation using infrared thermography by Maniar *et al.* (2015) proposes that negligible variations in T_{sk} exist within both peripheral and central regions of interest under thermoneutral resting conditions. This may support the suggestion that in the absence of sweat differences between conductive and infrared devices are a product of conductive device fixation. In the included studies where conductive overestimation of T_{sk} was consistently observed, the microenvironment created by fixation to the skin was most likely the primary cause of higher T_{sk} directly below the measurement probe (Buono and Ulrich, 1998; Psikuta *et al.*, 2013; Tyler, 2011). This insulation of the measurement area impairs the skins capacity to remove heat immediately beneath the contact probe, artificially raising the T_{sk} readings. The extent to which tape influences temperature measurements varies on the amount applied (Tyler, 2011) and the type of tape used (Psikuta *et al.*, 2013) (e.g. adhesive woven fabric vs. permeable non-woven tape).

4.9 Limitations and Future Research

The current review involved an exhaustive search based on a comprehensive list of electronic databases and extensive supplementary searching. It was our intention to adhere to the PRISMA framework and guidelines for systematic reviews (Moher *et al.*, 2009); however, there were some limitations. Studies included in this review were restricted to English, and relevant data may have been overlooked in the unpublished grey literature. Additionally, two studies had data manually extracted from graphs and figures (Buono *et al.*, 2007; Chuang *et al.*, 1997). Although this was undertaken independently by two reviewers, with inconsistencies checked through consensus and a third party, it still serves as an estimation of the MD. It should also be noted that five of the included studies failed to report limits of agreement between methods of T_{sk} measurement (Buono *et al.*, 2007; Burnham *et al.*, 2006; Chuang *et al.*, 1997; Heimann *et al.*, 2013; Ruopsa *et al.*, 2009). This omission may influence conclusions drawn from the investigations. For example, LoA represents the distribution of the differences between two methods and theoretically a spread of data in both equally positive and negative directions outside of the clinically significant ± 0.5 °C MD can cancel each other out leaving a MD of 0.0 °C, suggesting perfect agreement across the sample. This was seen in the study by Kelechi *et al.* (2011) it was reported that 12 of the 17 measurements taken between a thermistor and infrared thermometer were outside the clinically important MD (± 0.5 °C) yet the overall sample MD was 0.2 °C. However, this limitation would simply reinforce the findings of the current review as the five studies which reported acceptable agreement (MD < ± 0.5 °C) without a LoA could in fact have substantial distribution of MD in both positive and negative directions and bring the agreement between devices into question (LoA > ± 1.0 °C).

The paucity of research comparing device measurement accuracy along the limits of the human T_{sk} continuum is also concerning. Therefore, it should be a priority of researchers to investigate devices under severe environmental and physical conditions where measurement accuracy is critical for minimising potential injury (i.e., frost bite, heat stress, burns). Therefore, future research should compare and contrast differences between an assortment of commonly used conductive and infrared devices throughout the human T_{sk} range, during rest, exercise and recovery, under different ambient conditions – particularly cold exposure and cryotherapy – to better understand the limitations and sources of error between conductive and infrared devices. Further to this, research examining if differences between devices are exacerbated between gender, varying health status, population (young vs. elderly; lean vs. obese) and/or ethnicity is warranted.

5 Conclusions

Human T_{sk} is commonly assessed in various clinical, sporting, occupational and research settings. This review sought to systematically evaluate the agreement between conductive and infrared devices in the assessment of T_{sk}. The current evidence base suggests that infrared thermometers and conductive devices adequately agree when individuals are at rest in a thermoneutral environment.. However, infrared cameras do not agree with conductive devices in a similar environment. In the presence of extrinsic (i.e. hot environments) or intrinsic factors (i.e. pathology, exercise) the agreement in infrared thermometers is lost and augmented differences become apparent in infrared cameras compared to conductive devices. However, an inherent limitation in the current evidence is the high risk of bias and the current conclusions are not definitive based on poor methodological quality and small sample sizes. Future quality, well reported research in this area is required.

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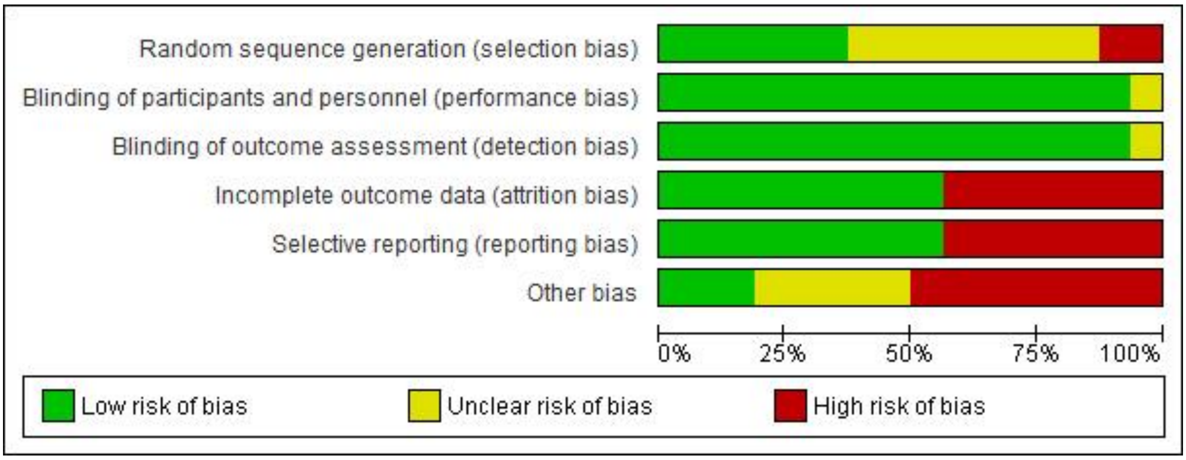
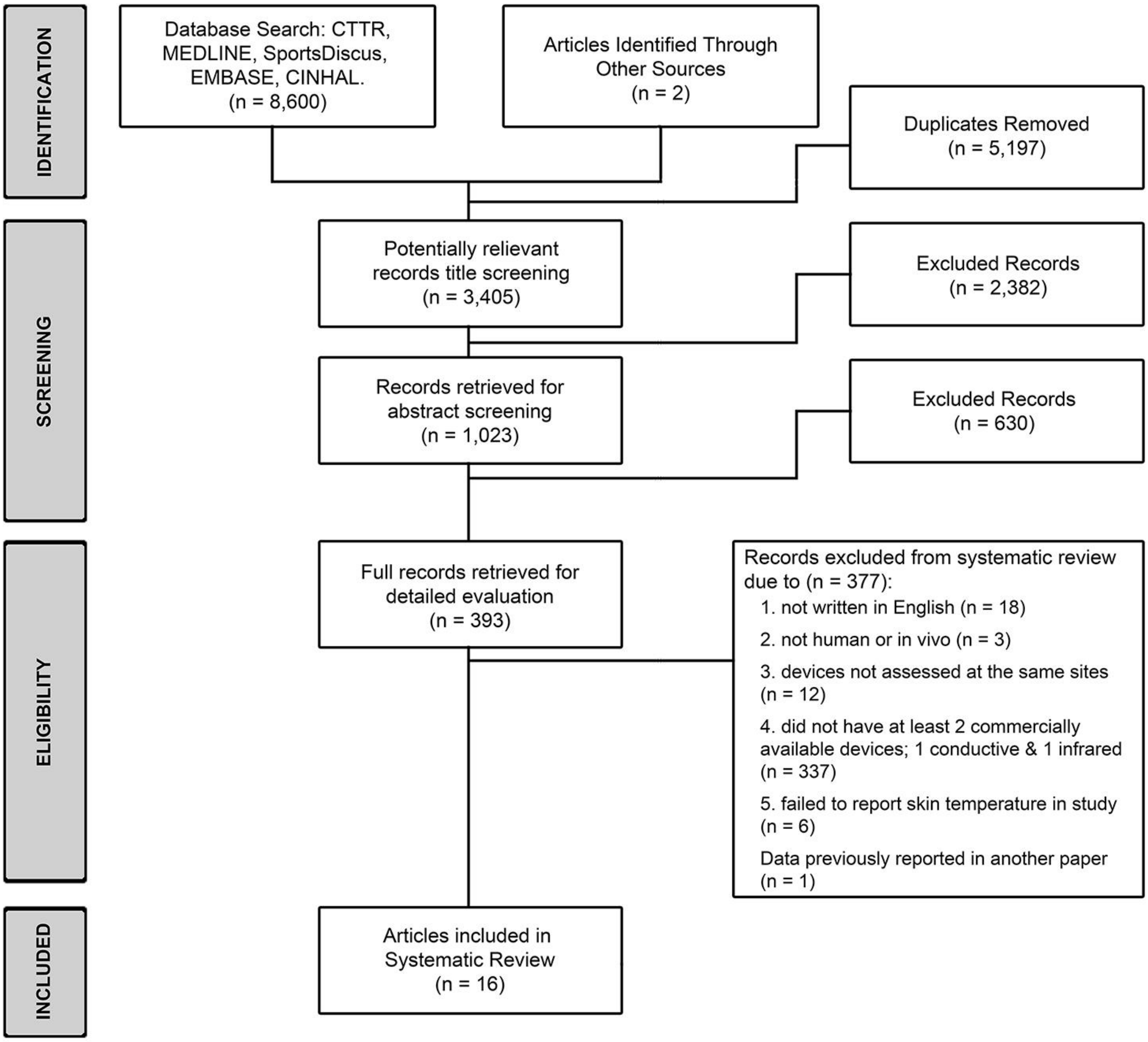

Random sequence generation (selection bias)
Blinding of participants and personnel (performance bias)
Blinding of outcome assessment (detection bias)
Incomplete outcome data (attrition bias)
Selective reporting (reporting bias)
Other bias
0%
25%
50%
75%
100%
Low risk of bias
Unclear risk of bias
High risk of bias


IDENTIFICATION
Database Search: CTTR, MEDLINE, SportsDiscus, EMBASE, CINHAL. (n = 8,600)
Articles Identified Through Other Sources (n = 2)
Duplicates Removed (n = 5,197)
SCREENING
Potentially relievant records title screening (n = 3,405)
Excluded Records (n = 2,382)
Records retrieved for abstract screening (n = 1,023)
Excluded Records (n = 630)
ELIGIBILITY
Full records retrieved for detailed evaluation (n = 393)
Records excluded from systematic review due to (n = 377):
1. not written in English (n = 18)
2. not human or in vivo (n = 3)
3. devices not assessed at the same sites (n = 12)
4. did not have at least 2 commercially available devices; 1 conductive & 1 infrared (n = 337)
5. failed to report skin temperature in study (n = 6)
Data previously reported in another paper (n = 1)
INCLUDED
Articles included in Systematic Review (n = 16)

Study or Subgroup	Infrared Mean [°C]	Infrared SD [°C]	Infrared Total	Conductive Mean [°C]	Conductive SD [°C]	Conductive Total	Mean Difference 95% CI [°C]
Bach et al. (2015)							
Rest: TM vs. IT	32.07	0.74	330	31.72	0.67	330	0.35 [0.24, 0.46]
Rest: TN vs. IT	32.07	0.74	330	31.74	0.71	330	0.33 [0.22, 0.44]
Rest: TM vs. IC	32.56	0.79	330	31.72	0.67	330	0.84 [0.73, 0.95]
Rest: TN vs. IC	32.56	0.79	330	31.74	0.71	330	0.82 [0.71, 0.93]
Exercise: TM vs. IT	34.89	0.6	330	35.33	0.73	330	-0.44 [-0.54, -0.34]
Exercise: TN vs. IT	34.89	0.6	330	35.6	1.08	330	-0.71 [-0.84, -0.58]
Recovery: TM vs. IT	32.21	0.72	450	31.16	1.06	450	1.05 [0.93, 1.17]
Recovery: TN vs. IT	32.21	0.72	450	31.53	1.22	450	0.68 [0.55, 0.81]
Recovery: TM vs. IC	33.04	0.74	450	31.16	1.06	450	1.88 [1.76, 2.00]
Recovery: TN vs. IC	33.04	0.74	450	31.53	1.22	450	1.51 [1.38, 1.64]
Buono et al. (2007)							
Rest: 15 °C	27	2.1	12	27.2	1.5	12	-0.20 [-1.66, 1.26]
Rest: 25 °C	32.4	1.6	12	32.1	0.9	12	0.30 [-0.74, 1.34]
Rest: 35 °C	36	0.9	12	35.1	0.3	12	0.90 [0.36, 1.44]
Exercise: 15 °C	26.5	0.9	12	26.6	1.6	12	-0.10 [-1.14, 0.94]
Exercise: 25 °C	31.8	0.7	12	32.3	0.8	12	-0.50 [-1.10, 0.10]
Exercise: 35 °C	35.5	0.5	12	35.4	0.2	12	0.10 [-0.20, 0.40]
Burnham et al. (2006)							
All Sites: IT1	31.4	1.6	34	31.9	1.6	34	-0.50 [-1.26, 0.26]
All Sites: IT2	31.7	1.7	34	31.9	1.6	34	-0.20 [-0.98, 0.58]
Fernandes et al. (2014)							
Rest: 15th minute	32.54	0.4	12	31.78	0.47	12	0.76 [0.41, 1.11]
Exercise: 30th minute	31.58	0.58	12	32.8	0.62	12	-1.22 [-1.70, -0.74]
Recovery: 30th minute	32.53	0.32	12	31.59	0.54	12	0.94 [0.58, 1.30]
Heimann et al. (2013)							
Site: Back	35.86	0.62	200	35.91	0.48	200	-0.05 [-0.16, 0.06]
Site: Upper Abdomen	36.21	0.62	200	36.92	0.36	200	-0.71 [-0.81, -0.61]
James et al. (2014)							
Rest: 10th minute	33.06	0.65	14	33.81	0.44	14	-0.75 [-1.16, -0.34]
Rest: 20th minute	33.04	0.81	14	33.93	0.52	14	-0.89 [-1.39, -0.39]
Rest: 25th minute	33.06	0.83	14	34.1	0.43	14	-1.04 [-1.53, -0.55]
Rest: 30th minute	33.27	0.67	14	34.1	0.39	14	-0.83 [-1.24, -0.42]
Rest: 35th minute	33.31	0.8	14	34.16	0.41	14	-0.85 [-1.32, -0.38]
Exercise: 4th minute	32.63	1.13	14	34.75	0.5	14	-2.12 [-2.77, -1.47]
Exercise: 8th minute	33.45	0.54	14	35.26	0.31	14	-1.81 [-2.14, -1.48]
Exercise: 12th minute	33.26	0.85	14	35.19	0.31	14	-1.93 [-2.40, -1.46]
Exercise: 16th minute	33.33	0.94	14	35.19	0.4	14	-1.86 [-2.40, -1.32]
Exercise: 20th minute	33.32	0.99	14	35.25	0.56	14	-1.93 [-2.53, -1.33]
Johnstone et al. (2012)							
Exercise: 20 °C	33.8	1.5	10	33.8	1.2	10	0.00 [-1.19, 1.19]
Exercise: 30 °C	35.4	1	10	35.9	1.1	10	-0.50 [-1.42, 0.42]
Kelechi et al. (2011)							
Rest: 10th minute	30.9	1.6	17	30.7	1.8	17	0.20 [-0.94, 1.34]
Rest: 20th minute	31.3	1.8	17	31.2	2.9	17	0.10 [-1.52, 1.72]
Cold Application: 10th minute	23.2	2.9	17	22.9	0.5	17	0.30 [-1.10, 1.70]
Kelechi et al. (2006)							
Day 1: Left Leg	32.57	1.7	55	32.71	1.75	55	-0.14 [-0.78, 0.50]
Day 1: Right Leg	32.51	1.79	55	32.41	1.67	55	0.10 [-0.55, 0.75]
Day 2: Left Leg	32.59	1.58	55	32.75	1.5	55	-0.16 [-0.74, 0.42]
Day 2: Right Leg	32.58	1.46	55	32.5	1.4	55	0.08 [-0.45, 0.61]
Day 3: Left Leg	32.72	1.51	55	32.72	1.49	55	0.00 [-0.56, 0.56]
Day 3: Right Leg	32.68	1.55	55	32.47	1.32	55	0.21 [-0.33, 0.75]
Roy et al. (2006)							
Site: Left L4	33.54	0.77	525	32	0.78	525	1.54 [1.45, 1.63]
Site: Right L4	33.47	1.05	525	31.86	0.9	525	1.61 [1.49, 1.73]
Site: Left C4	33.66	0.74	525	32.42	0.97	525	1.24 [1.14, 1.34]
Site: Right C4	34.39	1.51	525	32.72	1.49	525	1.67 [1.49, 1.85]