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Abstract

Background

Severe thermal discomfort may increase risk of drowning due to hypothermia or hyperthermia from prolonged exposure to noxious water temperatures. The importance of using a behavioral thermoregulation model with thermal sensation may predict the thermal load that the human body receives when exposed to various immersive water conditions. However, there is no thermal sensation "gold standard" model specific for water immersion. This scoping review aims to present a comprehensive overview regarding human physiological and behavioral thermoregulation during whole-body water immersion and explore the feasibility for an accepted defined sensation scale for cold and hot water immersion.

Methods

A standard literary search was performed on PubMed, Google Scholar, and SCOPUS. The words “Water Immersion,” “Thermoregulation,” “Cardiovascular responses” were used either as independent searched terms and MeSH terms (Medical Subject Headings) or in combination with other text words. The inclusion criteria for clinical trials terms to thermoregulatory measurements (core or skin temperature), whole-body immersion, 18-60 years old and healthy individuals. The prementioned data were analyzed narratively to achieve the overall study objective.

Results

Twenty-three published articles fulfilled the review inclusion/exclusion criteria (with nine measured behavioral responses). Our outcomes illustrated a homogenous thermal sensation in a variety of water temperatures ranges, that was strongly associated with thermal balance, and observed different thermoregulatory responses. This scoping review highlights the impact of water immersion duration on human thermoneutral zone, thermal comfort zone, and thermal sensation.

Conclusion

Our findings enlighten the significance of thermal sensation as a health indicator for establishing a behavioral thermal model applicable for water immersion. This scoping review provides insight for the needed development of subjective thermal model of thermal sensation in relation to human thermal physiology specific to immersive water temperature ranges within and outside the thermal neural and comfort zone.

Keywords: thermal perception, thermal sensation, whole-body immersion, thermoregulation, temperature ranges

1. Introduction

Extreme environmental conditions during whole-body water immersion increases the risk of dangerously high and low body temperatures, in which thermosensation and feelings of euphoria/dysphoria are important indicators of thermal load for physicians since early times (Galen, *De Sanitate Tuenda*; Calthrop 1928). Thermal injuries occur in extreme ranges of water conditions, that are dependent on water temperature and immersion duration, that can cause injuries such as frostbites, burns, and drowning (Kappel et al., 1997; Fujishima, 1986; Nimmo, 2004; An et al., 2019; Tipton et al., 2017). The first defense against maintaining normal body temperature and preventing thermal injuries from the external environment is behavioral thermoregulation via skin thermoreceptors and perceptual feelings, that signal the brain to behaviorally thermoregulate. These behaviors include moving environmental location such as escaping from a hot or cold pool or changing clothes, increasing fluid intake, and self-selecting intensity of swimming work rate (Flouris and Schlader, 2015: Guéritée et al., 2014). *Thermal perception* is defined as the mental state of how

a person experiences ambient temperature and is composed of two basic elements: thermal sensation and thermal comfort (Lv et al., 2017; Flouris and Schlader, 2015). The thermal sensation is the conscious state of distinguishing hot and cold stimuli, while thermal comfort is the mental state related to ambient temperature satisfaction (Aizawa, 2019; Chatonnet and Cabanac, 1965; Olausson et al., 2005; Lv et al., 2017; Flouris and Schlader, 2015). Therefore, a major emphasis should be given to thermal perception as a dominant behavioral driver for health and aquatic safety because it could be used to prevent the dangerous thermal loads that a human body receives in a variety of environmental conditions (Hayasaka et al., 2010). However, the current models of thermal sensation and comfort relate to ambient conditions. There is a current gap in knowledge on how these relate to immersion in hot or cold water temperatures.

The thermal subjective evaluation involves a common neurophysiological mechanism. While current understanding of whether transient receptor potential ion channels (TRP) are thermostats or thermosensors, it is widely accepted that TRPs play a key role in thermoregulation for humans and other mammals (Kobayashi, 2015; Li, 2017, Romanovsky, 2007; Tan and Knight, 2018; Wang and Siemens, 2015). In general, the heat signal transduction through skin TRPs to specific brain regions controls many physiological and cognitive functions (Flouris and Schlader, 2015; Romanovsky, 2007; Wang and Siemens, 2015). Some of the TRPs are implicated in temperature sensation, thermoregulation, and metabolism, in which body and skin temperature are the primary inputs to mediate cutaneous vasodilation and vasoconstriction. In the case of TRPM8 ion channels, their reaction depends either on the initial vascular tone or on the release of vasopressor or vasorelaxant transmitters such as norepinephrine, neuropeptide Y, and nitric oxide (NO) (either from sensory neurons or endothelial cells) (Charkoudian, 2010; Johnson et al., 2009; Pan et al., 2018).

Specifically, water immersion triggers both thermal and tactile sensation, in a unique manner, altering the tone and electrical activity of the somatosensory cortex, in which its action is to recognize the quality of thermal stress (Aizawa, 2019; Lv et al., 2017; Nimmo, 2004). However, it remains unknown how thermal perception in water is similar or different to over large variations of air temperature spectrums.

Under steady-state ambient conditions, it is well understood that thermal comfort zone (TCZ) (ASHRAE 55, 2013), defined as the perception and state of mind that

expresses satisfaction within the thermal environment, is within a temperature range known as the thermoneutral zone (TNZ) (Glossary of terms for thermal physiology, 1987). However, an increased functional metabolic rate higher than basal rate or an exposure in a non-uniform environment may alter the broadening of the TCZ (Zhang et al, 2010; Kingma et al., 2014, 2017). The TNZ is the zone described as the temperatures where heat is lost without regulatory changes in basal metabolic heat production or evaporative heat loss; this zone is deemed equal to heat gain in respect to the basic law of thermodynamics (Eq. 1) (Pallubinsky et al., 2019; Shapiro and Epstein, 1984; Epstein and Moran, 2006). Notably, TCZ and TNZ share the same goal for preserving body temperature, where skin and core temperature dictate the ranges, but behavioral regulation is modified outside the TCZ, and autonomic regulation is active outside the TNZ. (Kingma et al., 2014). Moreover, the upper and lower limits of TNZ are affected by complex interactions of vasomotor, metabolic rate, body insulation, sex, acclimatization, and microclimate (Pallubinsky et al., 2019; Kingma et al., 2014; Scweiker et al., 2018). The TCZ for ambient air temperatures has been described to be between 28 and 30°C and the TNZ are between 28 and 32 °C for a naked person (Hardy and Dubois, 1938). It is important to highlight that most of the literature on the TCZ and TNZ has been studied in various ambient air conditions. Only one study has reported a very narrow range in TNZ during 60 min of immersion in water temperature between 35.0 and 35.5 °C (Craig and Dvorak, 1968).

$$S\,[W] = (M \pm W) \pm (K + R + C) \pm (Cres - Eres) - E$$

Eq. 1 reflects the mathematical expression that describes the rate of change of body heat (gain or loss) (S) of the human body based on the First Law of Thermodynamics. Expressed in watts [W]. M = metabolic rate; W = mechanical work rate; K = conductive heat transfer; R = radiant heat exchange; C = convective heat transfer. Respiratory heat dissipation is determined by (Cres – Eres) expressing the water loss form respiratory tract where Cres = dry respiration heat loss; Eres = latent respiratory heat loss; E = heat loss by evaporation of sweat.

During exposure to water immersion, only the lower critical temperature limit (LCT), and not the upper critical temperature limit (UPL), is utilized for the critical water temperature (CWT), and also derived from the critical air temperature as mentioned in the Scholander's classical theory of TNZ (Wakabayashi et al., 2008;

Rennie et al., 1962). CWT reflects a water temperature between 28-34^{o}C, in which a nude man can tolerate a 3hr prolonged water immersion without appearing shivering-thermogenesis (Rennie et al., 1962). According to Yermakova's biophysical model, this neutral spot is in view with a 35^{o}C mean skin temperature and agrees with other related articles (Shapiro and Epstein, 1984; Fanger, 1970; Tipton et al., 2017). Due to the 25 times higher thermal conductivity of water, the thermoneutral point for water has been reported to be near ~34^{o}C; however for ambient air, it is ~30^{o}C (Dogaru and Radulescu, 2015; Yermakova et al., 2013; Nadel et al., 1971; Kingma et al., 2017). Hence, the thermoneutral aquatic equilibrium may differ among different concepts of thermoneutrality (CWT vs Biophysical model). However, based on the data available, the thermoneutral zone for water is unknown, as UPL remains unspecified, and may also differ from immersion duration and ambient air TNZ. Additionally, most data on the TNZ are based on small animals' physiological responses; however, few studies have examined both human physiological (i.e., core and shell temperature) and behavioral parameters (i.e., thermal perception) (Pallubinsky et al., 2019; Kingma et al., 2014; Scweiker et al., 2018), but more understanding is needed in the context of water exposure.

A common practice for assessing subjective perception is using thermal scales (Lee et al., 2010; Lundgren et al., 2014; Schweiker et al., 2017). Many challenges regarding the constructions and use of such a scale need to be addressed including the unit change of scale and vocabulary selection may be influenced by language and culture (Auliciems, 1981; Lee et al., 2009, 2010; Tochihara et al., 2012; Pantavou, 2020; Schweiker et al., 2017). In general, people are unable to recognize more than seven levels of sensations without error (Miller, 1967). Therefore, ASHRAE 55 (2013) incorporates a seven-point thermal sensation scale and a four-point thermal comfort scale as introduced by Gagge (1967). Another overlooked barrier is that the central thermal sensation descriptors located below or above thermoneutral mark may cause confusion by users (Peña Fernández et al., 2019; Schweiker et al., 2017). Thus, semantics and connotations, which characterize a thermal scale or thermal concept, may "lead" to errors in interpretation of specific words or phrases with the same meaning, and likelihood to make invalid logical assumptions (Auliciems, 1981; Cabanac 1988, 2020; Schweiker et al., 2020). These errors may reduce the accuracy of using thermal comfort models as they relate to body and skin temperatures (Jacquot et al., 2014; Cheng et al., 2012; Zhao et al., 2021).

The major question is if *the criteria are objectively or subjectively set to define the water temperature as cold or warm* and *are they related to the thermoregulation of the human body during whole-body immersion in healthy individuals*? Water temperature classifications have numerous landmarks (climatology, human physiology), in which the body temperature is the primary benchmark in the domain of Medical Hydrology – Balneology (see Table 1) (Castany, 1963; Pentecost et al., 2003, 2005; Thurner, 1967; Kappelmeyer and Haenel, 1974; Messina et al., 1999; Varga, 2010). A similar attempt was made by spa specialists, who vaguely synthesized a more complex thermal classification based on thermal subjective judgment (Table 2), whose practicality recommended exclusively for educational purposes in the domain of Balneology and Hydrotherapy (Ledo, 1996). No "gold standard" thermal sensation scale exists to correlate with water and body temperatures. Most importantly, no water temperature scale has considered that thermosensitivity and thermal perception are time-dependent variables.

The main purpose of this study was to provide an overview of thermoregulation and thermal feelings during whole-body water immersion, taking into account the current state of knowledge of human thermoregulatory (skin temperature, core temperature, sweating, shivering thermogenesis, cardiovascular system) and neurocognitive responses (thermosensitivity, thermal sensation). We attempted to clarify the thermal dose effect of hydrotherapy, and evaluated the literature on water duration immersion water temperatures. We chose the scoping review as the most suitable method for a deeper understanding of the logic behind thermal sensation and physiological homeostasis with the aim of examining the feasibility of determining scales related to water as cold or warm (Auliciems, 2014).

2. Methods

The approach was a mixed method scoping literature review as referred by Arksey and O'Malley (2005). The central research inquiry was human thermoregulatory responses (e.g., core temperature, skin temperature, thermal subjective assessment) during whole-body water immersion. The main outcome was to outline thermal sensation scales, in a variety of water temperatures and reviewing references temperatures for colder or warmer air and water temperatures. PRISMA-ScR checklist was completed (Table 3).

2.1 Inclusion & exclusion criteria

The target sample included healthy individuals between 18-60 years old. The inclusion criteria for clinical trials in relation to thermoregulatory variables (core or skin temperature), tap water immersion from the diaphragm level up to the xiphoid sternum in normal-weighted subjects with total fat percentage 20-30% or body mass index 18.5-24.99kg/m^2, and 40-60% relative humidity (*Rh*). To investigate the range of thermal feeling in water, we summarized a variety of water chemical compositions such as carbonated baths. We exclude studies that used visual analog scales, partial water immersion, water-perfused suit, or referred to animal studies, case reports, conference papers, posters, dissertations, and editorials. Lastly, we performed a review to the literature for relevant articles that were identified to meet articles within the inclusion criteria.

2.2 Search Strategy and screening

The literary search was reviewed through Medline/PubMed, Google Scholar, and SCOPUS. There was no restriction on language and date. The key terms "Water Immersion," "Thermoregulation," "Thermosensing physiology," "Cardiovascular responses" were used either as sole searched terms and MeSH terms (Medical Subject Headings) or in combination with other text words (Table 4). We repeated the search strategy to all databases. The articles were screened according to title and abstract, and then the duplicates were removed through Zotero. The final selected articles were read in full-text.

2.3 Data extraction and analysis

Data extraction methods range based on the type of study and data displayed. The first author MN extracted and charted the following thermoregulatory data from each article: author(s), year of publication, country, total size of sample, modalities, core and skin temperature, thermal descriptors, and water duration immersion. Experienced exercise physiologist specializing in biochemical and physiological outcomes BD assessed and reviewed the water immersion protocols reported in each study. The articles were not blinded during the extraction and charting process. Formal analysis applied by the thermal physiologist ER with the aim of examination heat balance during immersion using the available raw data from Craig and Dvorak (1968). The prementioned data were analyzed narratively to achieve the overall study objective.

3. Results

Fig. 1 represents the flowchart of the scoping review (PRISMA flow diagram), and Table 5 characterized the in vivo studies relating to thermoregulatory responses in water. In total, 23 articles were included after the removal of the duplicates and screened selection from a total of 411 articles (Craig and Dvorak, 1968; Lee et al., 1997; Wakabayashi et al., 2008; Becker et al., 2009; Kappel et al., 1997; Maeda et al., 2001; Watanabe et al., 2006; Sato et al., 2004; Sato et al., 2009; Nishimura et al., 2002; Nakamura et al., 1996; Rodriques et al., 2020; Kojima et al., 2018; Fujisima, 1986; Allison and Reger, 1992; O'Brien et al. 2000; Stephens et al. 2014; Solianik et al. 2014; Mansfield et al. 2021; Hohenauer et al., 2020; Rivas et al., 2016; Hashiguchi et al., 2002; Tochihara et al., 1998). Ten articles came from Japan, 7 articles from USA, 2 articles from Australia, 1 article from Lithuania, 1 article from United Kingdom, 1 article from Switzerland, and 1 article from Denmark. A schematic example of human heat balance and thermoneutral zone is presented in Fig. 2 after 30 min of immersion with thermal sensation based on retrieved data.

3.1 Summary of thermoregulatory responses during water immersion

In water temperature of 20-36^{o}C, the skin temperature approached that of water temperature with a deviation of ~0.5^{o}C (Craig and Dvorak, 1968; O'Brien et al., 2000; Lee et al., 1997; Wakabayashi et al., 2008; Becker et al., 2009; Kappel et al., 1997; Sato et al., 2009; Nishimura et al., 2002; Montgomery, 1974). However, the core temperature responded differently between 20-31.3^{o}C and 32-36^{o}C. At 20-31.3^{o}C, the internal temperature decreased steadily over time (O'Brien et al., 2000; Lee et al., 1997; Wakabayashi et al., 2008; Becker et al., 2009; Lee et al., 1997). The rate of change differed between two extreme thermal ranges. At 24^{o}C, there was a significant drop of 0.3^{o}C from the initial value in the first 30 min, followed by a steady downward trend. After two hours of immersion, the core temperature dropped ~1^{o}C (Lee et al., 1997; Wakabayashi et al., 2008). In contrast at 31.3^{o}C, esophageal temperature inclined 0.3^{o}C in the first 12 minutes, and thereafter it decreased gradually (Becker et al., 2009). In 32-37^{o}C water temperature ranges, no changes were observed in core temperature even after 2 hours (Keppel et al., 1997; Weston et al., 1987). However, in water temperature of 38-42^{o}C, the non-immersed neck skin surface temperature increased to 35.5^{o}C rapidly within the first 10 minutes, while the

surface skin temperature of immersed body parts fell 1°C below of water temperature (Cannon and Keatinge, 1960; Hayward and Keatinge, 1981; Rodrigues et al., 2020; Mansfield, 2021; Stephens et al., 2014). Water over 40°C significantly increased the core temperature after the first 30 minutes reaching 38.3°C, and in two hours of immersion, it continued to increase up to 39.5°C (Allison and Refer, 1992; Kojima et al., 2018; Weston et al., 1987; Fujishima, 1986; Miwa et al., 1994; Mansfield, 2021; Rivas et al., 2016). These data reflect the thermal responses in normal-weighted subject.

Several shifts in thermal responses occurred in cold water temperature <20°C (O'Brien et al., 2000; Solianik et al., 2014). At a water temperature of 15-18°C, the core temperature remained stable for the first half-hour before decreasing ~ 0.5°C (Cooper et al., 1976; Hayward and Keatinge, 1981; O'Brien et al., 2000; Kaupinen, 1989; Lee et al., 1997; Tarlochan and Ramesh, 2005; Tikuisis et al., 1988, 2000; Solianik et al., 2014). The surface skin temperature rapidly reached the water temperature within the first ten minutes at 15-20°C (O'Brien et al., 2000; Bradford, Gerrard, and Cotter, 2019; Hayward and Keatinge, 1981; Tikuisis et al., 1988; Yermakova et al., 2013). In colder water (<10°C) skin temperature of the immersive parts increased up to ~5°C above water temperature (Hohenauer et al., 2020; Hayward and Eckerson, 1984), but Cannon and Keatinge (1960) found out that skin was just within about 1°C of water temperature – probably different instruments (ibutton vs wirable thermistors) and the use or not of a waterproof taping may explain this discrepancy of temperature data. According to Tipton and colleagues (2017), immersion in cold water 10-15°C cause many changes, and is dependent on duration and is characterized as 1) in the first three minutes, the surface of the skin cooled, 2) in 3-30 minutes, neuromuscular cooling provoked, 3) for more than 30 minutes the phenomenon of hypothermia appeared, and 4) death coincides with core temperature at ~28°C and 5) the lower the temperature and the longer the immersion duration are, the greater is the risk of frostbite.

3.2 Summary of thermal sensation relating to water temperature ranges

Only 9 out of 23 included articles evaluated thermal sensation (TS) along with water immersion duration (see Table 5), though none of the experimental trials occurred in water <18°C. The ASHRAE 7-point scale was utilized by two Japanese research groups (Sato et al., 2004; Nishimura et al., 2002), a 13-point scale was chosen only by

Wakabayasi et al. (2008), a 9-point scale according to ISO 10551 was preferred by one Swiss, two Australian, and two Japanese research groups (Rodrigues et al., 2020; Stephens et al., 2014; Mansfield et al., 2021; Hashiguchi et al., 2002; Tochihara et al, 1998), while a 13 point McGinnis perception scale, which contained sensation and comfort descriptors, preferred by one American research group (Rivas et al., 2016). This discrepancy of thermal scales may limit the interpretation around thermal perception due to a potential bias error (Schweiker et al., 2017; Lee et al., 2009).

In table 5, specific thermal characterizations were highlighted by the researchers, for example water ranges between 5-26^{o}C was determined as cold (Craig and Dvorak 1968; Lee et al., 1997; Wakabayashi et al., 2008; O'Brien et al., 2000; Stephens et al., 2014; Solianik et al., 2014; Hohenauer et al., 2020), while at 27^{o}C water was characterized as hot only by the Craig and Dvorak (1968). In the study of Wakabayashi et al. (2008) thermal sensation was measured every 5 minutes during a 60 min immersion at 26^{o}C water, in which the volunteers felt cool for the first 10 minutes, cold in the 35th minute, and severe cold in the 60th minute. Becker et al. (2009) referred water temperature of 31^{o}C as cool. In addition, in the research of Nakamura et al. (1996) participants perceived the water at 30^{o}C to be slightly cool within 10 minutes of immersion. The neutral "range" of thermal sensation was predefined between 34-36^{o}C by the majority of authors (Becker et al., 2009; Kappel et al., 1997; Sato et al., 2009; Nishimura et al., 2002; Kojima et al., 2018), except by Stephens et al. (2014) that described it as warm. However, all volunteers of the included papers experienced neutral sensation in the water temperature between 34-35 ^{o}C within 20 minutes of water immersion (Sato et al**.,** 2009; Nishimura et al., 2002; Stephens et al., 2014). Some researchers described the water at 39 ^{o}C as warm (Craig and Dvorak 1968; Becker et al**.,** 2009), while some others as hot (Kappel et al**.,** 1997; Watanabe et al., 2006; Rivas et al., 2016); nonetheless, the participants felt warm within the first 30 minutes of immersion between 38-42^{o}C (Nakamura et al., 1996; Rodriques et al., 2020; Mansfield et al., 2020; Rivas et al., 2016). Notably, contrary to the actual data of thermal sensation, a common arbitrary definition of water temperatures >40^{o}C has been reported as hot among researchers. (Nakamura et al., 1996; Rodriques et al., 2020; Mansfield et al., 2020; Rivas et al., 2016).

Most importantly, there are gaps in knowledge in understanding thermal sensation at different water temperatures in relation to ambient air environment

temperatures outside of the TNZ. During warm water immersion (>38^{o}C) in a room temperature ranged from 5-30^{o}C, whole-body thermal sensation was "warm", but at 35^{o}C air temperature the thermal sensation was characterized as "hot" (Hashiguchi et al., 2002; Mansfield et al., 2020; Miwa et al., 2021; Rivas et al., 2016; Rodriques et al., 2020; Tochihara et al., 1998). To our knowledge, no data are available for thermal sensation responses at colder water temperatures in different ambient conditions.

3.3 Summary of thermoregulatory responses at different water temperature ranges during CO_2 water immersion

The literature findings showed that CO_2 water immersion at 35°C caused a statistically significant drop in core temperature with parallel elevation of skin blood flow, while core temperature increased in a water >39°C. (Nishimura et al., 2002; Sato et al.,2009). The core temperature significantly increased above 38°C water-due to enormously evaporative loss and increased blood flow in CO_2 water compared to exposure in tap water at the same temperature (Watanabe et al., 2006; Sato et al., 2004). It has been reported that CO_2 water modified thermal sensation after an acute whole-body immersion expressed by a "slightly warm" feeling at 35°C, while a cooler sensation was felt when exposed in tap water (Nishimura et al., 2002; Sato et al., 2009).

4. Discussion

The main objective of this review was to present a comprehensive overview regarding human physiological and behavioral thermoregulation during whole-body water immersion. In Table 5, the vivo studies relating to thermoregulatory responses were reviewed (Craig and Dvorak, 1968; Lee et al., 1997; Wakabayashi et al., 2008; Becker et al., 2009; Kappel et al., 1997; Maeda et al., 2001; Watanabe et al., 2006; Sato et al., 2004; Sato et al., 2009; Nishimura et al., 2002; Nakamura et al., 1996; Rodriques et al., 2020; Kojima et al., 2018; Fujisima, 1986; Allison and Reger, 1992; O'Brien et al., 2000; Stephens et al., 2014; Solianik et al., 2014; Mansfield et al., 2021; Hohenauer et al., 2020; Rivas et al., 2016; Hashiguchi et al., 2002; Tochihara et al., 1998). In Fig. 2 the characterization of a thermal balance, thermoneutral zone, and thermal sensation at different water temperatures are described. The results illustrated 1) that the responses of thermoregulation and thermal sensation among various water temperature varied and differed from ambient air temperatures and 2) different

thermoregulatory and thermal sensation responses between tap and CO_2 water immersion. The most important issue in this scoping review was the gaps in knowledge on water immersion duration on human TNZ and TCZ, and thermal feeling.

4.1 Nature of thermal sensation: subjectivity vs objectivity

Currently there are no common accepted definition for cold and hot water temperatures (Tipton & Bradford, 2014). Difficulty in the interpretation was identified for the meaning of sensation and perception. There is a need to use objective criteria that can separate physical responses from conscious interpretation that is strongly dependent on personal and environmental circumstances (Auliciems, 1981). Additional issues may be from a deterministic approach, in the case of thermal sensation, which can be biased by psychology and physiology perspectives (Auliciems, 1981). Behavioral thermoregulation development will require reliable thermal scale with higher correlation coefficient in the field and laboratory studies than the usual Bedford and ASHRAE scales (Auliciems, 1981; Gagge et al., 1967; Schweiker et al., 2017).

Gagge (1967) sought to understand the nature of thermal sensation through the Aristotelian work *Little Physical Treatises*, in which only five senses were identified (sight, hearing, smell, taste and touch) (Hicks, 1907). However, Gagge disregarded the quotes 423b29-32, 424a10-11 from *On the Soul/De anima*, in which the philosopher stated that thermal sensation was a property of touch dominated by the body. Gagge suggested that Galen was the first person to have recognized the relationship of touch and thermal feeling; however according to Aristoteles (*On the soul*, frag. 427b27-428b17), he was the first to describe each sensation (thermal sensation) that comes from its own aesthetic organ (unknown at the time, temperature sensors - TRPs) suggests a true feeling with a minimum degree of error, while sensations that may be derived from recalling a prior memory or guessing a feeling without applying the physiological stimuli (temperature) suggests a fantastic pseudo-feeling with the most part false (Hicks, 1907).

Indeed, Aristoteles' scope of view agrees with the results of this review regarding thermal sensation, as we observed same thermal expressions between

bathers-participants during a period of time but not always among observants for various water temperature ranges. The key component is the criterion of time and quality of feeling (real vs imaginary) for investigating the nature of thermosensitivity. Similar verbal anchors were used by other researchers and participants, for example the 42^{o}C water immersion was characterized hot not only by authors, but also by subjects at the 45th min of immersion (Rodrigues et al., 2020; Rivas et al., 2016). The subjective nature of thermal sensation is also different between researcher's reference point. Also, the subjectivity coexists in participants' expression, as leading question, number of categories on the scale, and words that describe the units may affect thermal choice, for example there may be a difficulty for choosing between slightly cool or neutral (Schweiker et al., 2017; Peña Fernández et al., 2019). However, the objective support for thermal sensation is using the subjective thermal scales in relation to water immersion temperature, ambient air exposure, and skin and core temperatures, and heat balance status (Sato et al**.,** 2009; Stephens et al., 2014; Nakamura et al., 1996; Nishimura et al., 2002; Rodriques et al., 2020; Mansfield et al., 2020; Rivas et al., 2016). Most importantly, the change in magnitude of skin and core temperature and thermal heat loss or gain status (heat balance), and efferent and afferent inputs to the hypothalamus would affect thermal sensation responses (Craig, 2002; Vanos et al., 2010; Tikuisis et al., 1998).

4.2 Neutral zone, and thermal sensation during water immersion

The concept of TNZ is essential for improving gaps in knowledge about behavior thermoregulation within the concept of whole-body water immersion (Kingma et al., 2017). Indeed, neutral sensation coincided with a comfortable feeling and thermal balance (Auliciems, 1981; Calthrop, 1928; Chatonnet and Cabanac, 1965; Gagge et al., 1967; Kingma et al., 2017). Specifically, heat gain is balanced with heat loss during thermal neutral sensations (Gagge et al., 1967; Kingma et al., 2017; Montgomery, 1974). Heat balance during immersion of different water temperatures diverge at distinct time points govern thermal sensation. More specifically, we noticed that TNZ during 30 minutes of immersion varied from 30-36^{o}C (Fig. 2), but for longer immersion duration limits it varied from 35.5-36.0^{o}C (Craig and Dvorak, 1968). This means that thermoneutral feeling was apparent within TNZ, mainly in its center, as can be seen in Table 5 (Kingma et al., 2017). Non-shivering thermogenesis was aligned with a cool sensation and shivering thermogenesis with a cold sensation, both

of which have been reported below LCT (Tikuisis et al., 1998; Montgomery et al., 1974; Wakabayashi et al., 2008; Rennie et al., 1962). Warm sensation was apparent above UCT that represented the increased heat metabolic rate accompanied by cardiovascular changes (Gagge et al., 1967; Kingma et al., 2017; Rivas et al., 2016). According to CO_2 water studies, TNZ may vary compared to tap water, since CO_2 provokes vasodilation to limbs rising blood flow; and therefore influences the body core and skin temperatures.

4.3 Initial thermal status determines the thermal sensation

Clinical research has shown that thermal perception was sometimes correlated with skin temperature and other's with core temperature (Aizawa, 2019; Calthrop, 1928; Chatonnet and Cabanac, 1965; Enescu, 2019; Nielsen and Nielsen, 1984; Rodrigues et al., 2020; Wakabayashi et al., 2008; O'Brien et al., 2000). In general, both the environmental conditions and the individual's initial thermal state temperature may influence the thermal perception (Goto et al., 2006; Oi et al., 2017). When the individual was already at rest, thermosensitivity was positively correlated with skin temperature and ambient temperature (in ambient air, water immersion) (Aryal and Becerik-Gerber, 2019; Craig and Dvorak, 1968; Nielsen and Nielsen, 1984; Stephens et al., 2014). The initial thermal status may explain discrepancies of thermal sensation from several physiological thermoregulatory inputs. Hyperthermia activates brain centers and other neural pathways between the hypothalamus, the cortical sensory cortex that may prevail after passive heating and activate the endogenous opioid system that is responsible for exercise-induced analgesia (Oi et al., 2017; Yuan et al., 2016; Fujimoto et al., 2021).

Whole-body thermal sensation during exercise in hot air temperatures is deemed to be blunted, however local skin thermal sensation was not affected by the dynamic changes of core temperature (Flouris and Schlader, 2015; Fujimoto et al., 2021). It is unknown if exercising in water (swimming) has similar responses for thermal sensation and requires more research. Thermal sensation may become a practical tool for assessing the thermal stress, and a crucial factor for designing an applicable life-support system. In addition, thermal modeling revealed that the most critical body regions for heat loss are head and extremities (Montgomery, 1974; Yermakova et al., 2013). Further research is needed to investigate which part of the human body is the

most sensitive to local skin thermal perception for a variety of water immersion duration and metabolic conditions (e.g., rest, swimming).

4.5 Concerns about thermal scales

From a methodological point of view, we should be cautious in the interpretation of sensation as scale's validity uncertainty exists whether thermal sensation or thermal guessing is measured. Contrary to Schweiker et al. (2017), we strongly believe that number of categories should not be underestimated as they may contain bias. The end and middle-scale effect can confuse the participants (Boateng et al., 2018; Lantz, 2013). For example, when someone takes a little more time to decide which thermal category fits to his state best, we should be aware about the validity of his answer, whether it reflects explicit his sensation or thought. Evaluation process of thermal sensation triggers, except from the concrete underlying neural network for decoding warm or cold stimulus, the right fronto-parietal and anterior insula, which constitute the neural network attention (Nagashima et al., 2022). However, the kind of thermal scale (Likert-scale or visual analog scale) could influence the activity of the prementioned regions leading to another answer.

5. Limitations

The thermal conductivity is a crucial factor not only for thermal balance, but also for thermal sensation. In thermal carbonated mineral baths, human experienced water hotter than noncarbonated mineral water (Dogaru and Radulescu, 2015; Gutenbrunner et al., 2010), while seawater baths alternated osmolality that caused sweating evaporation and following producing a cooler sense compared to tap water (Tsuchiya et al., 2003). The quality of the thermal and non-thermal afferent may enable specific cascade pathways from TRPs determining sequentially thermal homeostasis and, behavioral thermoregulation (Olausson et al., 2005; Wang and Siemens, 2015; Weyer-Menkhoff et al., 2019; Zimmermann et al., 2011). Activation of these TRP ion channels can be derived from temperature, pH, and chemicals, e.g., CO_2, H_2S, H_2O_2 (contained in some thermal springs) (Dogaru and Radulescu, 2015; Gutenbrunner et al., 2010; Mori et al., 2017; Varga, 2010; Wang and Siemens, 2015). As mentioned previously, the time and temperature may influence the rate of temperature change for

skin and core during water immersion and therefore may influence the TNZ and TCZ and thermal perception due to the heat gain or loss.

5. Conclusions

This scoping review explores the nature of thermal sensation and the criteria for thermal classification. To date, attention has been directed to assess thermal comfort, especially in cold water, because of its links with detrimental incidents such as loss of consciousness, frostbite, and drowning (An et al., 2019; Tipton et al., 2017; Bradford, Gerrard, and Cotter, 2019). The thermal sensation variability can be explained, by the belief that water temperature assessment is a deep internal cognitive and experienced personal matter of interpretation (Calthrop, 1928; Chatonnet, and Cabanac, 1965a; Guéritée et al., 2015; Tipton and Bradford, 2014). New knowledge about TRPs function within the concept of TNZ and TCZ has provided an integrated physiological and psychological understanding of how thermoreceptors modify our thermal sensation and that are influenced by both the mind and body (Oi et al., 2017; Lv and Liu, 2007; Li, 2017; Wang and Siemens, 2015; Weyer-Menkhoff et al., 2019).

For the first time to our knowledge, is reviewed the support of literature on thermal sensation during whole-body water immersion and in the context of homogenous sensation and body thermoregulation parameters. The findings provide the importance of thermal sensation as an indicator for health and aquatic safety and as a principal factor for establishing a more complex predictive thermal comfort model applicable for water immersion (Cheng et al., 2012; Montgomery, 1974; Morishima et al., 2020; Streblow, 2011; Yermakova et al., 2013; Wissler, 2012). Further research is needed to construct an accurate thermal sensation scale for estimating both water temperature and thermal stress during water exposure in addition to how it is compared to ambient air temperatures.

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Highlights

- Re-evaluation the feasibility of an accepted definition for cold and warm water.
- First review of the literature on behavioral and physiological thermoregulation during water immersion in a range of temperatures.
- Thermal sensation and thermoneutral zone are time and temperature dependent.
- Understanding thermal sensation specific to water immersion will be valuable for prescriptions used by aquatic health professionals.

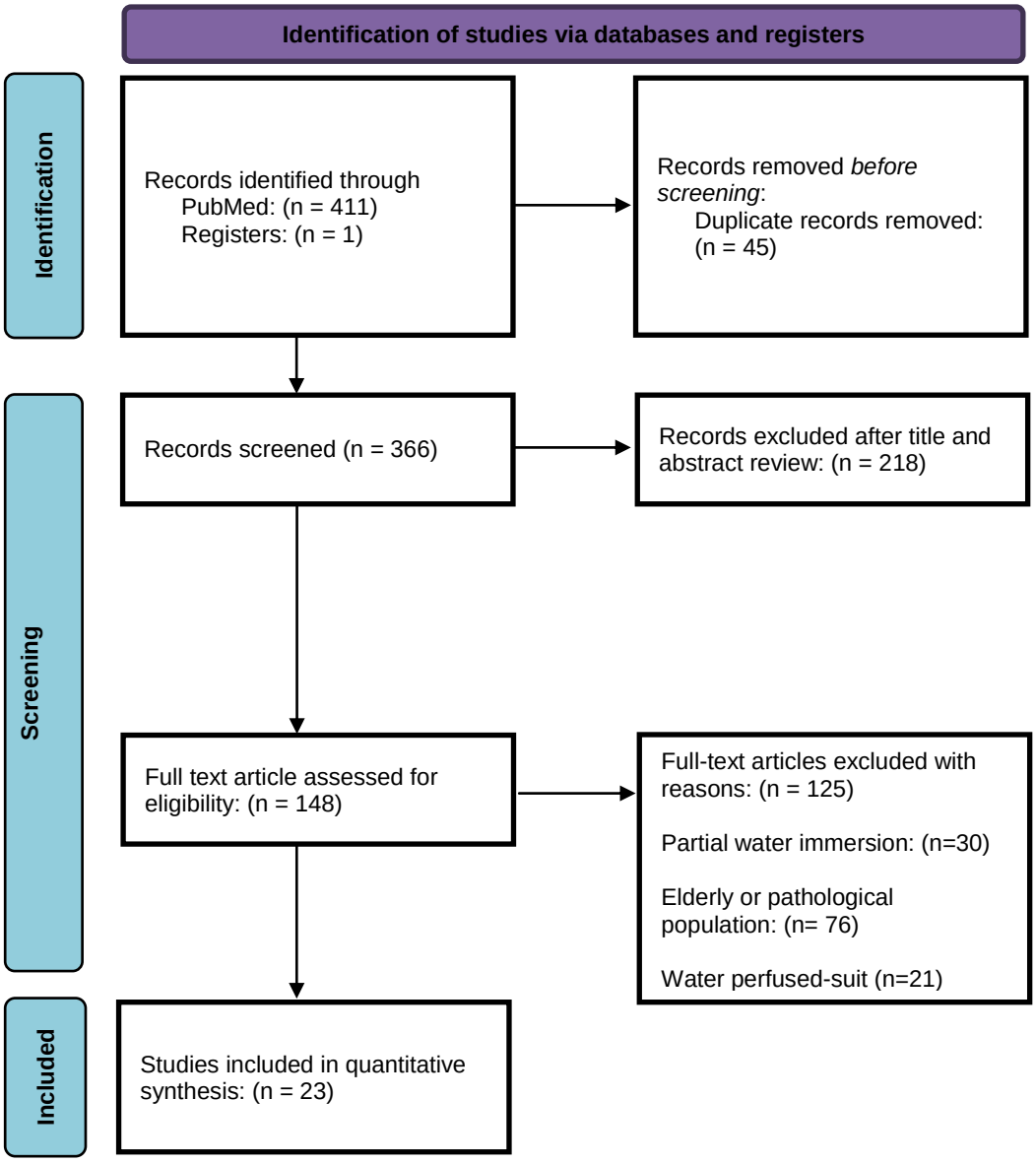

Fig. 1 Flowchart scoping review

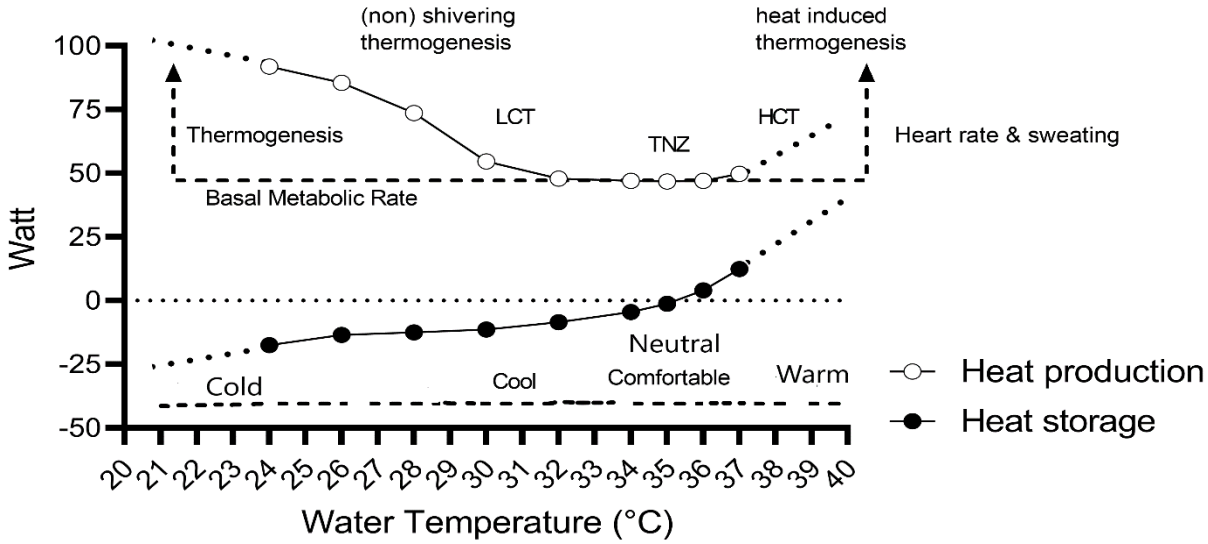

Fig. 2 depicts the relationship between thermal balance, thermoneutral zone, and thermal sensation after 30min of water immersion (Modified Table 2 from Craig and Dvorak, 1966). Thermoneutral zone (TNZ) is the range of water temperatures associated with basal metabolic rate required to support minimal life functions, and water loss. Below the lower critical temperature (LCT), metabolic rate increases to maintain body core temperature. Above the upper critical temperature (UCT), water loss increases due to cardiovascular regulatory blood volume distribution to skin and sweating and may coincide with heat-induced thermogenesis (e.g., Q10 effect: metabolic rate scales with tissue temperature according to Arrhenius law).

1139 **Table 1** Water thermal classification systems

Marotta (1933)	Thurner (1967)	Kappelmeyer –Haenel (1974)
Hyperthermal springs >38ºC	Hot springs >32ºC	Hyperthermal springs >38ºC
Mesothermal springs 30-40ºC	Warm springs 32ºC	25- Mesothermal springs 34-38ºC
Hypothermal springs 20-30ºC	Slightly warm springs 25ºC	20- Hypothermal springs 20-34ºC

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1150 **Table 2** Thermal perception scale for hydrotherapeutic use related to water temperature
1151 ranges

Ledo (1996)
very cold (0-12^{o}C)
cold (12-18^{o}C)
fresh (18-27^{o}C)
neutral (27-32^{o}C)
warm (32-36.5^{o}C)
hot (37-40^{o}C)
very hot (40-43^{o}C)

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1154 **Table 3** Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for
1155 Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	1-2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	2-5
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	5
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	6
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	6
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	6
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	6
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	6
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	7
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	6
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data	7

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
		synthesis (if appropriate).	
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	7
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	7
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	7
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	8
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	8-10
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	9
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	10-14
Limitations	20	Discuss the limitations of the scoping review process.	14
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	14-15
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	N/A

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1158 **Table 4** Search Terms for Medline

Heading	Search Strategy
Water Immersion	(balneology) OR (hydrotherapy) OR (whole-body immersion) OR (bath) OR (icy water) OR (cold water) OR (cool water) OR (thermoneutral water) OR (warm water) OR (hot water) OR (hot springs) OR (thermal springs) OR (carbon dioxide water) OR (carbonated water)
Thermoregulation	(thermosensing/physiology) OR (behavioral thermoregulatory responses) OR (thermoregulation) OR (thermal perception) OR (thermal sensation) OR (thermal scales) OR (core temperature) OR (body temperature) OR (tympanic temperature) OR (skin temperature) OR (shivering thermogenesis) OR (sweating) OR (TRP ion channels)
Cardiovascular System	(cardiovascular responses) OR (heart rate) OR (oxygen consumption) OR (skin blood flow) OR (oxygen saturation)

1159 Above searches combined with AND

1160

Table 5 In vivo studies relating to thermoregulatory responses

Authors (year)	Country	Total sample size	Modalities	Water Composition	Core temperature + Skin temperature	Descriptors of thermal qualities	Duration
Craig and Dvorak (1968)	United States of America	10	Head-out water immersion 24-36 ℃	Tap Water	Rectal temperature decreased at 24-36 ℃, tympanic temperature decreased only at 24-34℃ along time. skin temperature resembled water temperature	5-15℃ cold water, >27℃ warm according to authors	60min
Lee et al. (1997)	United States of America	8	Water immersion at different depths at 15℃ and 25℃	Tap Water	Rectal and esophageal temperature decreased significantly from 15th at 15℃ and in 30th minute at 25℃ from shoulder level	15-25℃ cold water according to authors	75min at 15℃/115 min at 25℃

Table 5 In vivo studies relating to thermoregulatory responses

Authors	Country	Total sample size	Modalities	Water Composition	Core temperature + Skin temperature	Descriptors of thermal qualities	Duration	s
Wakabayashi et al. (2008)	Japan	8	Water immersion at 29°C naked, and at 26°C with partial uniform	Tap water	Esophageal temperature decreased significant ~0.5°C at 35th minute for uniform condition, but not for naked	26 & 29°C cold water according to authors TS at 10min cool, at 35min cold, at 60min severe cold for both conditions TC at 10min and 35 min slightly uncomfortable, at 60 min uncomfortable for both conditions	60 min	
Becker et al. (2009)	United States of America	16	Water immersion at 31°C, 36°C, 39°C	Tap Water	Tympanic temperature increased significantly ~0.4°C only in warm water 39°C	31°C cool 36°C neutral 39°C warm according to authors	24 min	

Table 5 In vivo studies relating to thermoregulatory responses

Authors	Country	Total sample size	Modalities	Water Composition	Core temperature + Skin temperature	Descriptors of thermal qualities	Duration
Kappel et al. (1997)	Denmark	8	Water immersion at 34°C and 39°C	Tap water	Rectal temperature reached 38°C at 30th min in hot water, and 39.5°C at the end of 2h, while no changes at 34°C	34 °C thermoneutral 39 °C hot according to authors	2 h
Maeda et al. (2001)	Japan	5	Water immersion at 41°C, xiphoid sternum level	Tap water vs artificial gas CO_2 water (1000ppm)	Skin forehead increased about 2°C (CO_2 water) vs 1°C (tap water) no changes appeared between breast and upper limb muscle temperature	41°C hot according to authors	15min
Watanabe et al. (2006)	Japan	27	Water immersion at 39°C	Tap water vs artificial CO_2 water (33ppm)	Skin forehead temperature increased significantly and muscle forearm at CO_2 water	39°C hot according to authors	10 min
Sato et al. (2004)	Japan	10	Water immersion at 40°C at the nipple level	Tap water vs artificial CO_2 water (1000ppm)	Tympanic temperature increased significant 0.3°C at CO_2 water, no changes in skin forehead and skin chest temperature	40°C hot according to authors	10 min

Table 5 In vivo studies relating to thermoregulatory responses

Authors	Country	Total sample size	Modalities	Water Composition	Core temperature - Skin temperature	Descriptors of thermal qualities	Duration
Sato et al. (2009)	Japan	10	Water immersion at 35°C at the nipple level	Tap water vs artificial CO_2 water (1000ppm)	Tympanic temperature decreased ~0.3°C at CO_2 water, no changes in tap water	35°C thermoneutral according to authors TS from 10min tended to slightly warm in CO_2 water vs neutral to slightly cool in tap water	20 min
Nishimura et al. (2002)	Japan	6	Water immersion at 35°C up to diaphragm level	Tap water vs artificial CO_2 water (1000ppm)	Tympanic temperature decreased 0.4°C at CO_2 water, while no changes in tap water	35°C thermoneutral according to authors TS slightly warm in CO_2 water vs neutral in tap water throughout the session	20 min
Nakamura et al. (1996)	Japan	12	Water immersion at 30°C and 38°C after submaximal exercise	Tap water	Rectal temperature no significant changes at 38°C and 30°C	no thermal descriptors by authors TS was slightly cool for 30°C and warm for 38°C	10 min

Table 5 In vivo studies relating to thermoregulatory responses

Authors	Country	Total sample size	Modalities	Water Composition	Core temperature - Skin temperature	Descriptors of thermal qualities	Duration
Rodriques et al. (2020)	Australia	30	Water immersion at 42^{o}C at the waist level	Tap Water	Rectal temperature increased 0.4^{o}C significantly from 15th minute, reached 38.7^{o}C at the end of session. Mean skin temperature increased at 35.5 ^{o}C within the first 30min.	42^{o}C hot according to authors TS in 10th min was warm, while in 45th min changed to hot	120 min
Kojima et al. (2018)	Japan	8	Head-out immersion at 35^{o}C and 42^{o}C	Tap Water	Esophageal temperature increased significantly 2^{o}C at the end of the 42^{o}C session.	35°C neutral and 42^{o}C hot according to authors	15min
Fujisima (1986)	Japan	11	Water immersion at 43^{o}C at the chin level	Tap Water	Oral temperature increased 1.6^{o}C at the end of session, while mean skin temperature increased at 39.4^{o}C.	43^{o}C hot according to author Thermal sensation was measured according to an arbitrarily scale. No data shown.	8 min

Table 5 In vivo studies relating to thermoregulatory responses

Authors	Country	Total sample size	Modalities	Water Composition	Core temperature - Skin temperature	Descriptors of thermal qualities	Duration
Allison and Reger (1992)	United States of America	6	Water immersion at 40^{o}C at the nipples level	Tap Water	Esophageal temperature increased significantly 0.75^{o}C at the end of the session.	40^{o}C hot according to authors	21 min
O'Brien et al. (2000)	United States of America	14	Water immersion at 20^{o}C at the shoulder level	Tap Water	Rectal temperature decreased 0.83^{o}C at the end of the session.	20^{o}C cold according to authors	60min
Stephens et al. (2014)	Australia	39	Water immersion at 18^{o}C and 35^{o}C at the level of the C7 vertebrae	Tap Water	Core temperature did not changed significantly during cold water immersion, while it increased from the 5th min, differentiated 0.5^{o}C at the 10th from the initial value during hot immersion. Skin temperature resembled the water temperature	18^{o}C cold and 35^{o}C hot according to authors TS remain stable for both conditions; TS was neutral for 35^{o}C immersion and cold for 18^{o}C immersion	15min

Table 5 In vivo studies relating to thermoregulatory responses

Authors	Country	Total sample size	Modalities	Water Composition	Core temperature - Skin temperature	Descriptors of thermal qualities	Duration
Solianik et al. (2014)	Lithuania		Water immersion at 14^{o}C to the manubrium level	Tap Water	Rectal temperature decreased 1^{o}C at the end of the session.	14^{o}C cold according to authors	170min
Mansfield et al. (2020)	United Kingdom		Water immersion at 42^{o}C to the belly level	Tap Water	Rectal temperature increased 0.4^{o}C significantly from 15th minute, reached 38.7^{o}C at the end of session. Mean skin temperature of the immersed local parts increased at 41 ^{o}C	42^{o}C hot according to authors TS in 15th, 30th min was warm, while in 60th min changed to hot TC in 15th,30th min was comfortable while in 60th min uncomfortable	60min
Hohenauer et al. (2020)	Switzerland		Water immersion at 10^{o}C to the sternum level	Tap Water	Regional surface skin temperature reached `14^{o}C	10^{o}C cold according to authors	10min
Rivas et al. (2016)	United States of America		Water immersion at 39^{o}C to the clavicle	Tap Water	Rectal temperature increased ~0.4^{o}C	39^{o}C hot according to authors TS in 20th minute was	60min

Table 5 In vivo studies relating to thermoregulatory responses

		level		significantly from 20th minute, reached 38^{o}C at 30th minute and ~38.5^{o}C at the end of session. Mean skin temperature of the immersed local parts increased at 38 ^{o}C	"warm but fairly comfortable", in 30th minute was "uncomfortable warm", while in 60th minute was 'hot"	
Hashiguchi et al. (2002)	Japan	Water Immersion at 40^{o}C to the sternum level at different air temperatures (10°C, 17.5°C, 25°C)	Tap Water	Rectal temperature increased more (~0.1°C) at 25°C and 17.5°C air compared to 10°C (~0.05°C), Mean skin temperature affected by air temperatures.	40^{o}C hot according to authors TS was not influenced between ambient conditions (No thermal marker was reported in detail)	10min
Tochihara et al. (1998)	Japan	Water Immersion at 40^{o}C to the sternum level at different air temperatures (5°C, 10°C, 15°C, 20°C, 25°C, 30°C, 35°C)	Tap Water	Mean Skin Temperature affected by air temperatures	TS was slightly warm at 5°C, 10°C, 15°C, warm at 20°C, 25°C, 30°C and hot at 35°C)	8min