Chapter 7
Assessment of Sport Garments Using Infrared Thermography

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Abstract Sport garments and their properties directly influence the heat exchanges occurring at the interface between the human skin and the environment. Active skin cooling or warming through innovative apparel is more and more developed in training and competition. Infrared thermography can provide original insights into the patterns of skin temperature distribution during exercise that can then be used for clothing design using a bodymapping approach.

7.1 Introduction

Sport garments nowadays represent a necessary element for all types of physical activity across the world. Our ancestors used to run in the most simple attire fighting for survival, escaping from dangers or exhausting animals. Over the course of evolution, clothing has become a cultural as well as a safety requirement following trends of fashion and protecting the skin against potential external aggressors. Specific equipment and clothing have always accompanied the development of ancient and modern sports.

Sport garments manufacturers are engaged in a design process combining aesthetics and various functions in order to meet the sport demand as well as the body needs. Furthermore, there are sometimes some sport federation rules to comply with for authorization in competing events.

Sport garments are at the interface between the human body and the environment and therefore modify the heat and mass transfers occurring at the skin surface [1].

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In this context, clothing interacts with physiological and physical processes impacting skin temperature that can be assessed by infrared thermography. Over the last decade, much attention has been paid to regional thermoregulatory effector responses (e.g. bodymapping of local skin temperatures) in order to adapt the choice and location of material to better meet the body needs [1–4]. Thermal patterns obtained by infrared thermography with high spatial sensitivity become very convenient over contact measurements on the skin for mapping large body regions.

The assessment of sport garments, specifically their impact on the skin using this technique, enables great advances in the field of garment design and its consequence on sport performance and thermal comfort, both for recreational and professional athletes.

7.2 Sport Garments in Exercise Thermoregulation

7.2.1 The 6 Basic Parameters and Heat Balance Equation

Clothing belongs to the six basic parameters [5] contributing to the overall thermal load placed on the human body in a given condition. Air temperature, radiant temperature, relative humidity (rh) and air velocity are the four external determinants defining the environmental conditions. Additionally, metabolic rate (M) determines the amount of heat produced during sport and this must be adjusted for the external work (W) performed on the outside world.

The combination of the parameters determines the potential avenues for heat dissipation towards the environment and heat gain towards the athlete's body.

The human heat balance equation integrates the different physical heat transfers and provides a calculation (7.1) of heat storage at any specific heat production. Clothing influences the intensity of the heat transfers by conduction, convection, evaporation and radiation.

$$S = M - W - E - K - C - R \tag{7.1}$$

Equation 7.1. Heat balance equation. Where S = net heat storage (W m^{-2}), M = metabolic rate (W m^{-2}) W = external work performed (W m^{-2}, positive or negative), E = evaporative heat loss (W m^{-2}), K = conductive heat transfer (heat loss or gain) (W m^{-2}), C = convective heat transfer (heat loss or gain) (W m^{-2}), R = radiative heat transfer (heat loss or gain) (W m^{-2})

Depending on the climate, duration and intensity of the exercise, sport garments can either minimize or maximize these heat transfers with fixed properties or specific active technologies.

The human autonomic thermoregulatory system is able to deal with decreasing or increasing heat storage by triggering a series of effector mechanisms (vasoconstriction/shivering and vasodilation/sweating) in order to maintain core temperature within a safe range. Skin temperature and the signal transmission from skin thermoreceptors also plays a role in the effective effector responses together with central thermoreceptors.

7.2.2 Basic Clothing Properties

The first basic property is clothing insulation (expressed in m^2 K W^{-1} or m^2 °C W^{-1}). This corresponds to the heat resistance offered by the garment to dry heat transfer (conduction, convection and radiation). Insulation is highly dependent on the amount of air trapped in the material (e.g. textile fibres) and this correlates well with material thickness, modulated by fibre diameter [6].

Apparels for sport can be composed of several items organized in various layers depending on the climate. It is important to take into account the still air also trapped in the microclimate between the different layers of the ensemble. This microclimate can be thick or thin depending on the location (e.g. no air gap at the shoulders), the clothing fit or elements to tighten clothing onto the body. Chen et al. [7] observed that thermal insulation was the largest with an air gap of 0.6 cm in windy conditions. Nielsen et al. [8] measured higher local skin temperatures with a tight-fitting compared to a loose fitting inner layer in a 5 and 20 °C environment, advocating for minimizing air disturbance due to movements to maintain insulation.

Wind, posture and body motion are factors that can indeed greatly modify insulation by compressing the garment or by pumping the air between the different layers, therefore reducing the overall heat resistance [9]. ISO 11079 provides calculations on the required clothing insulation to stay in thermal equilibrium depending on the exercise intensity [10]. For example, clothing insulation of 0.155 m^2 K W^{-1} (= 1 Clo unit) would be necessary in a −20 °C environment whilst running.

Nowadays, garment insulation for cold weather sports comes from either goose down (especially in winter jackets) or from synthetic fibres made with hollow cores or air shafts in order to trap still air [11]. Porous aluminium coating/inner lining to reflect body heat or aerogel with high thermal performance for its thickness can also be used [12].

The second basic property is clothing evaporative resistance (expressed in m^2 kPa W^{-1}). It corresponds to the clothing ability to transfer moisture away from the skin surface. The vaporization of liquid sweat occurs at the skin or in the clothing layers [13]. Similar to heat resistance, evaporative resistance depends on material thickness (with its enclosed air) in the case of permeable materials. Coatings, membranes or other treatments on the garment greatly alter the transfer of vapour molecules to the environment. Some waterproof finishes close the fabric pores, therefore preventing external precipitation to wet the body but this also traps sweat inside the microclimate. For thin garments, the fibre characteristics also affect the diffusion properties and modify vapour resistance.

Other properties related to fibre type, yarn type and fabric construction influence heat and vapour transfers by reducing or enhancing parameters such as air permeability or moisture absorption [11]. Nielsen and Endrusick [14] measured the lowest skin temperature for an underwear having an open fishnet structure in a comparison with four other polypropylene knit structures in a two-layer clothing system at 5 °C.

In many different sports, especially in cold environments, a good compromise must be found between heat and vapour resistance. Sufficient insulation must ensure adequate cold protection before the exercise or during resting periods. At moderate to high workloads, heat production can largely exceed heat loss towards the environment and sweating takes place. Vapour resistance should therefore be small to avoid excessive moisture build up. Total clothing insulation was reduced by 20% when moisture content of the underwear was 100% of its dry weight [15] and wet clothing can lead to after chill.

Ventilation impacts the garment microclimate and can contribute to reduce the build up of non-evaporated or condensated moisture. This can occur through natural openings (at the neck, hands and lower end of a shirt or jacket) or specifically designed ventilation openings such as zippers across the torso, under the arms or at the sleeves. The combination of pit zip and side seam openings was the most effective in lowering skin temperature in outdoor jackets at 20 °C [16]. Zhang and Li [17] observed significant differences in mean skin temperature by modifying opening designs of T-shirt worn whilst running in a 25 °C environment. The bellows effect provided by slits in running jackets has found to be beneficial in terms of lowered skin temperature and improved thermal comfort [18, 19]. In situation of lower heat production or in colder environments, the reduced insulation induced by ventilation [20] must be prevented.

Waterproof membranes can be a requirement for outdoor sport garments in order to cope with snow or rain. Adverse weather can potentially lead to hypothermia, especially during long duration events with low heat production, as is the case of recreational hiking [21].

In summary, basic properties of clothing modify the heat exchanges at the skin/environment interface and therefore determine the level of skin temperature in a given environment. Some sports garments however influence skin temperature more actively and to a greater extent of cooling or warming during exercise.

7.2.3 Sport Garments and Skin Cooling

Skin temperature above 35 °C induces a perception of thermal discomfort [22] and has been found to be a critical factor to exercise performance [23]. Many cooling interventions have been explored for sport in hot weather conditions such as water baths, air exposure, drink ingestion, ice application both prior to [24, 25] and after exercise [26]. Practical aspects and cost of these strategies in real use are often questioned. Skin cooling can also be induced by sport garments during exercise with a direct impact on the cardiovascular, thermal and perceptual strain of recreational and professional sport enthusiasts.

Conductive cooling has been used through light-weight vest in different sports [27–29]. Mean skin temperature was significantly lower wearing the cooling jacket in a 32 °C 70% rh environment with an improved exercise time to exhaustion in male athletes [28]. Palm skin temperature was reduced by up to 1.5 °C wearing an ice vest (Flexi Cold Vest, Interspiro Ab, Lidingö, Sweden) made from water-filled cooling elements chilled at −20 °C before the exercise [29]. Neuromuscular fatigue and ventilatory responses were also lowered compared to a control trial with no vest in a 30 °C 40% rh environment leading to an increase of over 20% in running time. The seven male participants reported an improved thermal comfort throughout the exercise protocol [29]. During a 5 km running time trial in a 25 °C, 55% rh environment, master athletes also experienced improved thermal comfort with a cooling vest but performance was similar to the control condition [27]. The HyperKewl vest (TechNiche, Vista, California, USA) soaked with water and placed in the refrigerator (6 °C > 8 h) was worn during the whole time trial and it induced significantly lower skin temperatures especially at the trunk with up to 2 °C difference during the first half of the trial (Fig. 7.1) [27].

The efficiency of the cooling interventions relates to the surface area covered by the cooling garments as well as the ability to ensure a sufficient fit. In previous examples, the body surface area covered was approximately 0.20 m^2.

Conductive cooling has also been specifically targeted at the neck region. Despite its relatively small surface, the neck is an area of high allesthesial thermosensitivity [30, 31] and it can also be cooled effectively with minimal disruption

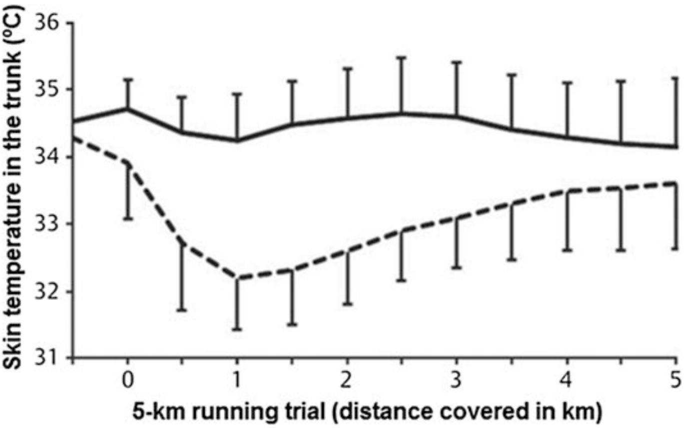

Fig. 7.1 Trunk skin temperature in master athletes during a 5-km running time trial in a control condition (*solid line*) and cooling vest condition (*dashed line*). Figure modifed from Eijsvogels et al. [27]

to sporting actions or attire [32]. Several studies have used a commercially available cooling collar (model CCX, Black Ice LLC, Lakeland, TN) frozen for 24–28 h (at −80 °C) in order to highlight its benefits for performance (time trials, repeated sprints) and perceived thermal strain in 30–32 °C 50–70% rh [32–35]. Neck skin temperature was reduced by up to 18°C during the first stage of exercise.

The integration of phase change materials (PCM) into adjustable packs for jackets represent another option to promote conductive cooling [36–38]. Skin temperature with a PCM vest can be reduced by up to 3–7 °C compared to without a vest in hot environments [36, 38].

Convective cooling was combined with PCM in order to enhance skin cooling in a hybrid system [39]. Four ventilation fans were incorporated into the clothing system with a maximum airflow of 0.012 m^3/s. Local skin temperatures were significantly reduced especially in the upper body (maximum reduction from 1 to 7 °C) compared to the control condition during a walking protocol in a 36 °C, 60% rh. The hybrid system was also effective in improving thermal and wetness perceptions in upper and lower body during both exercise and recovery periods [39].

Evaporative cooling was used through a lightweight garment made of hydrophilic fibres able to sustain water evaporation when wetted and consequently providing skin cooling [40]. During a running protocol in a 30 °C, 44% rh, this garment produced significantly lower mean and local skin temperatures by up to 2 and 5 °C respectively. Cooling the skin before the exercise elicited a reduced sweat loss whereas cooling during exercise reduced heart rate and the rate of perceived exertion. In both interventions, thermal comfort, thermal sensation and wetness perception were improved by mild evaporative cooling on the torso [40].

In the above cooling techniques, the lower skin temperatures enable a greater core-to-skin temperature gradient for dissipating heat from deeper regions of the body. Cardiovascular strain is reduced because less of the total cardiac output needs to be directed towards the skin, allowing more blood to be directed to active skeletal muscle.

All the above studies used only contact sensors to measure skin temperature in various body regions as well as mean weighed skin temperature calculations. Whilst being extremely useful to monitor the changes in skin temperature over time [41], contact sensors can not indicate the total extent of skin cooling over body regions. Moreover, point-to-point variation in local skin temperature can vary by as much as 7 °C over 5 cm [42]. Infrared thermography therefore represents a complementary tool to assess the efficiency of skin cooling especially because surface area is a key factor in the summation of autonomic and behavioural responses.

7.2.4 Sport Garments and Skin Warming

In cold environments, heat production during exercise is often sufficient to maintain total heat balance. However, extremities can be at risk of extensive cooling due to vascoconstriction. The clothing strategy is classically to choose the adequate insulation with multilayer garments including footwear, gloves and hats [43]. Nevertheless, the freedom of movement is key to many sports and increased bulk with increasing insulation should be avoided. Most of the examples below are more related to extreme industrial applications but the principles are now used in sport garments for enhanced local and overall thermal comfort.

Conductive warming through electrical heating was applied on the hands (heating wire on the fingers and back of hands covered by Arctic mitts) and separately on the torso (10 Kapton insulated flexible heaters) [44]. Finger skin temperatures were maintained at 28–35 °C in both conditions but torso heating (at 42 °C) contributed to an 8-time higher finger blood flow in a −25 °C environment.

In a less extreme context (2 °C, 80% rh) and using a walking protocol, Song and Wang [39] observed 2 °C higher skin temperatures at the stomach and back using an electrically heated vest (7 heating pads) compared to the same unheated vest. This was also true with a chemically heated garments composed of 14 non-reusable body warmers (iron powder, activated carbon, water, vermiculite and salt) for approximately the same surface as the heating pads. Both heated conditions induced improved whole body and local thermal sensations.

Conductive warming using PCM garments has been explored with simulation [45] or manikin studies [43] but no human testing to date.

Conductive and convective warming can be obtained through liquid warming garments such as the one designed for spacesuit with tubing over all body regions. This has proven to be effective in elevating skin temperatures especially in the fingers [46].

Some sport garments can also be worn at the end of the warm up phase or during recovery periods such as half time of team sport events. Faulkner et al. [47] demonstrated the benefits of conductive warming of lower leg muscles with heated trousers. This intervention increased local skin temperature and most importantly reduced the fall in muscle temperature (by approximately 1 °C), therefore preserving optimal power contractile properties for subsequent exercise performance. Similarly, Wilkins and Havenith [48] showed that a heated jacket worn between a swimming warm-up and the actual race can increase skin temperature and improve sprint swimming performance (Fig. 7.2).

Similar to cold conditions, infrared thermography could become useful to assess the spatial extent of skin warming in order to evaluate more precisely the efficiency of heating interventions or specific active garments during exercise.

7.3 Infrared Thermography Assessing the Influence of Sport Garments

The microenvironment between the skin and the inner-most layer of clothing affects skin temperature which, in turn, affects thermoregulatory responses. Skin temperatures should accurately assess the effectiveness of a clothing ensemble [11].

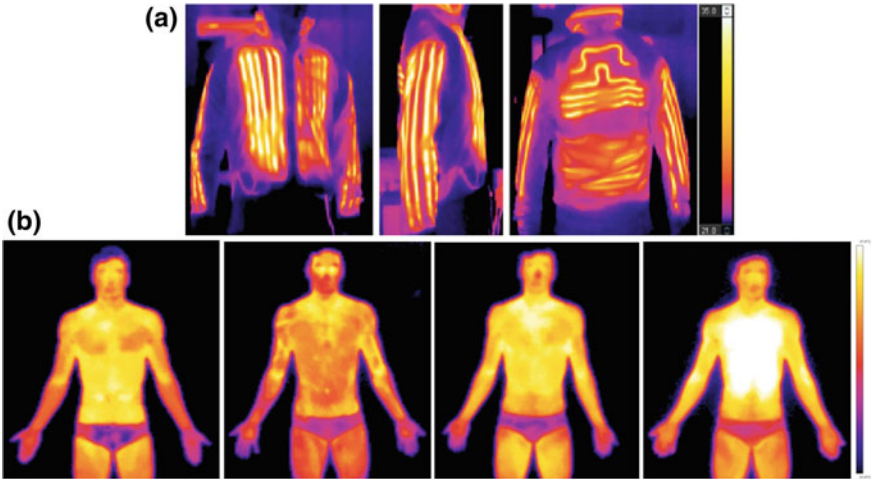

Fig. 7.2 **a** Thermography of the heated jacket. Figure obtained from Wilkins and Havenith [48]. **b** A sample of upper body thermograms from left to right: prior to warm-up, after warm-up, after recovery period for control and for heating. Temperature range 21–37 °C

Moreover, core temperature is rarely modified by sport garments and depends to large extent upon metabolic heat production. The concept of “thermal envelope” has then been suggested in order to evaluate the influence of sport garments in ecologically valid sports-related exercise protocols [49]. It refers to upper and lower limits in mean body temperature (from mean skin and core temperatures) elicited by clothing assemblies that could be worn under a given environmental conditions. Measuring skin temperature in various locations, especially in cool environments [50], is therefore highly important for this approach. Though infrared thermography can not track skin temperatures over time in clothed subjects, it provides the benefit of measuring large body surfaces with high-spatial resolution. Previous research has pointed out that skin temperatures and distribution immediately after undressing are the same as those which existed under the clothing [51, 52]. With careful data collection and standardized undressing procedures, this opens a wide area of testing the influence of many kinds of sport garments. The current knowledge in this field is presented with key examples in specific sports.

7.3.1 Assessment of Running Wear

Many studies have investigated skin temperature distribution of semi-nude runners using infrared thermography [4, 53–56]. Apart from the pioneering work from Clark et al. [54], no studies reported whole-body thermograms as they focused on specific body parts to understand the underlying mechanisms modifying skin temperatures between physiological (skin blood flow, muscle activation, body composition) and external factors (air and radiant temperature, air velocity, relative humidity). Fournet et al. [3] provided the first average whole-body thermograms based on a specific image processing technique [57] able to combine several thermograms of participants with a variety of body dimensions.

A quantitative and qualitative data analysis was provided on male and female runners with a special focus on the link between skin temperatures and skinfold thickness variations [57].

Using the same approach, Fournet [51] explored the thermal patterns of clothed runners at different stages of the exercise protocol. Twelve physically active males performed a 40-min running bout at 70% VO_{2max} in a 5 °C, 50% rh environment with frontal wind at 5 $m\ s^{-1}$. This was preceded by 5 min standing prior to exercise and followed by 10 min post-exercise recovery also standing on the treadmill with 2.8 $m\ s^{-1}$ frontal wind. Participants were wearing a one-layer tight-fitting winter long sleeves top and tights (Kalenji Isolate 4000, DECATHLON, France). Infrared thermography assessment was obtained at 4 different stages: prior to exercise (PRE), after 10 min of running (RUN10), after 40 min (RUN40) of running and after 10 min of recovery (POST); following a strictly controlled and short undressing procedure away from the wind. Whole-body thermograms (n = 12) are presented at stage RUN40 for the anterior and posterior body (Fig. 7.3).

Skin temperature underneath clothing was colder in regions such as the abdomen, pectorals, thighs, triceps, patella, neck and cheeks. They corresponded to regions deeply or poorly perfused, with large fat or muscle insulation, highly exposed to air velocity. The warm regions were located in the upper chest, spine, inner thighs, calves, elbow crease, popliteal fossa and orbits. They corresponded to regions with either high perfusion, low fat or muscle insulation and the natural creases of the human body where cross radiation exists between close surfaces or when surfaces are directly in contact.

A Y-shape of colder skin temperatures was noticeable over the anterior torso (pectoral and abdomen) and a Y-shape of warmer temperatures over the posterior torso (upper back and spine). Fournet [51] provided the general hypothesis of the compromise between the superficial blood flow and body characteristics (morphology and composition) to explain the skin temperature variations across the body. Hot spots in the upper chest, neck and upper back were strikingly in line with brown fat deposits in infants. As brown fat has been observed in adults especially in lean persons exposed to cold [58], it could be postulated that these regions contributed to specific warm spots due to their high vascularization and not necessarily due to their associated local thermogenesis.

Interestingly, mean skin temperature was similar in the clothed condition at 5 °C compared to the semi-nude condition at 10 °C [3]. The thermal patterns were almost identical between the conditions except for the warmer skin temperature at the upper chest and forearms (clothed) and at the calves and posterior legs (semi-nude). This could imply that heat dissipation is favoured close to heat production in the nude moving lower limbs. On the other hand, heat could be conveyed

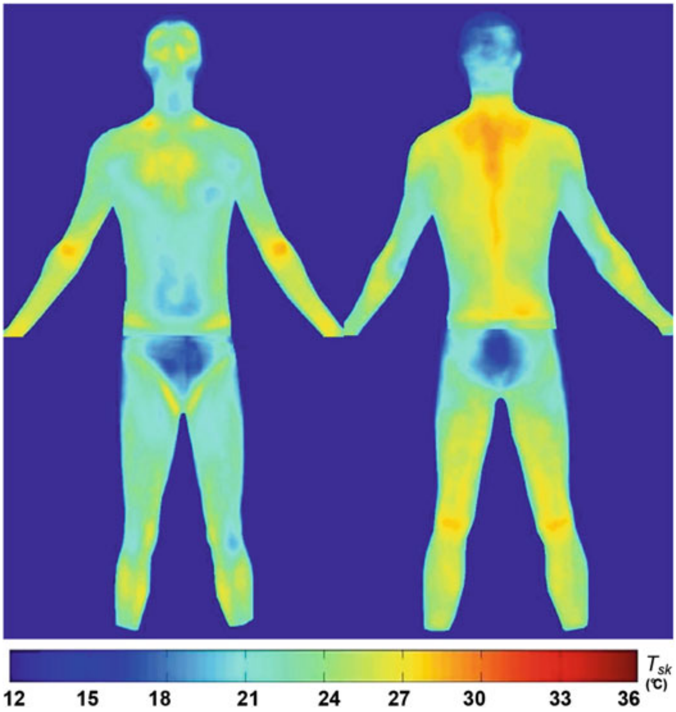

Fig. 7.3 Anterior (*left*) and posterior (*right*) group averaged whole-body maps of skin temperature after 40 min of running at 70% VO_{2max} in a 5 °C, 50% rh environment with uniform clothing insulation. Figure adapted from Fournet thesis [51]

back to the heart and then dissipated when quitting the aortic arch (upper chest) more intensively in a clothed condition.

Roberts et al. [4] investigated the thermoregulatory responses of 7 males wearing different base-layer garments during an intermittent running protocol. The base-layer hot was claimed to keep the wearer comfortably cool during exercise in warm environment whereas the base-layer cold garment was claimed to keep the wearer warm in cold conditions. These two garments with good wicking properties were compared to a 100% cotton base layer and bare-chested condition. Two running bouts lasting 23 min were repeated in a 20 °C, 50% rh environment on a treadmill with speeds varying from 6, 12 and 15 km h^{-1}. Mean, maximum, minimum skin temperatures were assessed based on the front and back torso area covered by the garments.

At the end of exercise, core temperature was similar between clothing conditions. On the other hand, mean skin temperature over the torso was the lowest in the bare-chested condition (28.5 ± 0.8 °C) followed by the base-layer hot (29.1 ± 0.4 °C). These were significantly lower than in the base-layer cold (29.8 ± 0.8 °C) and the 100% cotton garment (29.8 ± 0.8 °C). The thermoregulatory responses was associated with improved thermal comfort in bare-chest and base-layer hot condition compared to base-layer cold and cotton. Roberts et al. [4] postulated that this could be due to the low moisture retention in the lightweight base-layer hot (small yarn diameter, more interstices) therefore reducing skin wettedness, an indicator of thermal discomfort [6].

Some similarities in the thermal patterns were found such as the larger areas of higher temperature over the sternal region and the external oblique muscles of the abdomen. Thermal peaks could be observed in each condition and this is in line with previous work on semi-nude participants [55, 59] in connection with cutaneous perforators veins transferring blood from deep active regions [60]. The differences in evaporation and skin contact especially when garments became saturated could explain the significant differences between the conditions [4].

To date, this has been the only study exploring different clothing composition using infrared thermography to evaluate its impact on skin temperatures and the overall thermal pattern after running.

Priego Quesada et al. [61] conducted a specific study to point out the effects of graduated compression stockings on skin temperature after running. Forty two participants (29 males and 13 females) performed two running tests in a 24 °C, 50% rh lasting 30 min (10 min of warm up and 20 min at 75% of maximal aerobic speed) with and without compression in the lower leg. They hypothesized a direct influence of the covered body regions with extra insulation as well as a potential effect on areas with no garment contact. A quantitative analysis was performed based on a definition of several regions of interest (Fig. 7.4).

It was shown that running with compression stockings increased skin temperatures by 0.04–0.91 °C which could be due to the garment insulation. Moreover, skin temperatures in regions not covered by the stockings (vastus lateralis, abductor, semitendinosus) increased by 0.01–0.52 °C and it could be explained by a greater superficial perfusion induced by the lower limb coverage.

The knowledge of the thermal patterns under running apparels [4, 51, 61] could be extended to a myriad of clothing conditions and exercise types (continuous, intermittent, sprints, short/long distances) in order to map the similarities and differences in skin temperature distribution.

7.3.2 Assessment of Sports Bras

The influence of sports bras has mainly been studied in the field of biomechanics with the aim of reducing breast movement as well as exercise-related breast pain [62, 63]. This led to recommendations for the use of well-fitted and supportive sports bras while exercising. Ayres et al. [64] were the first to specifically investigate the influence of this clothing layer and composition on skin temperatures.

Eight females with C-cup breasts performed a short duration exercise protocol (20 min) in a 27 °C, 46% rh environment [64]. The protocol included a warm-up walk at 4 km h^{-1} (1% gradient) followed by 5 countermovement jumps and

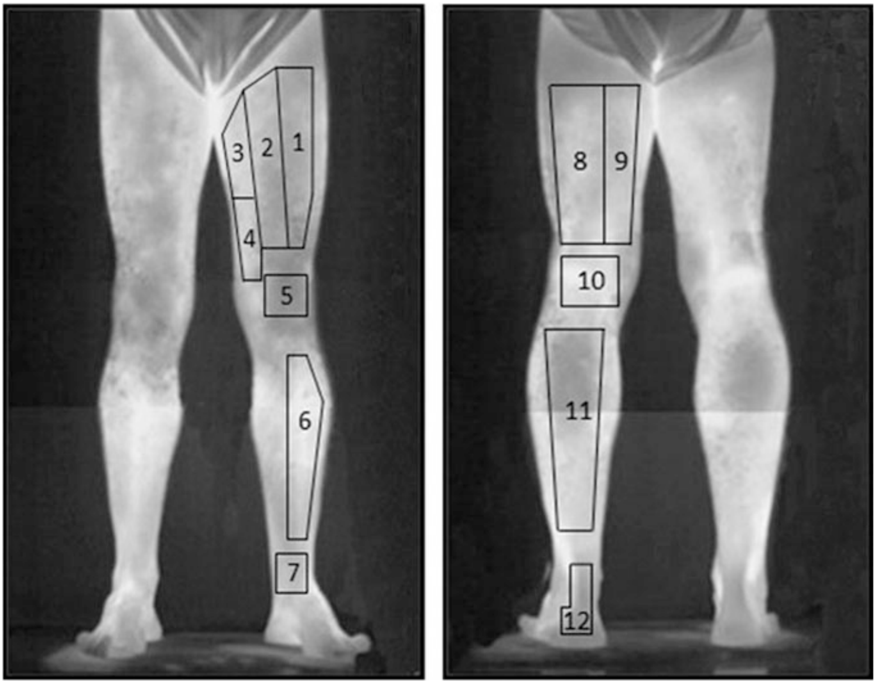

Fig. 7.4 Regions of interest for the evaluation of graduated compression stockings. *1* Vastus Lateralis. *2* Recture femoris. *3* Abductor. *4* Vastus medialis. *5* Knee. *6* Tibialis anterior. *7* Ankle anterior. *8* Biceps femoris. *9* Semitendinosus. *10* Popliteal. *11* Gastrocnemius. *12* Achilles. Figure obtained from Priego Quesada et al. [61]

5 maximum effort agility “T” test followed by 8 min of running at 10 km h^{-1}. They were either wearing a composite sports bra (65% Nylon, 22% Polyester 13% Elastane, Under Armour, Stability, USA) or polyester sports bra (100% Polyester, Under Armour, Strength, USA). The bare-breast and abdomen skin temperatures were assessed using infrared thermography before and immediately after exercise. Reflective markers were taped onto the skin in order to standardize the quantitative analysis with different regions of interest as shown on Fig. 7.5. The temperature of the left and right breast was averaged for each image. Results indicated that breast skin temperature was reduced to a lesser extent than abdominal skin temperatures (−0.6 vs. −2.1 °C) in both bra conditions demonstrating the reduced evaporative heat loss caused by the bra. This effect of insulation provided by the bra on breast skin temperature was also observed by Fournet et al. [3] during a running protocol in females.

In Ayres et al.’s study [64], bra composition had a significant influence on skin temperatures with a larger overall decrease in the polyester (−1.5 °C) compared to the composite sports bra (−0.9 °C). While bra comfort and bra fit were similar between conditions, participants reported greater thermal comfort in the polyester

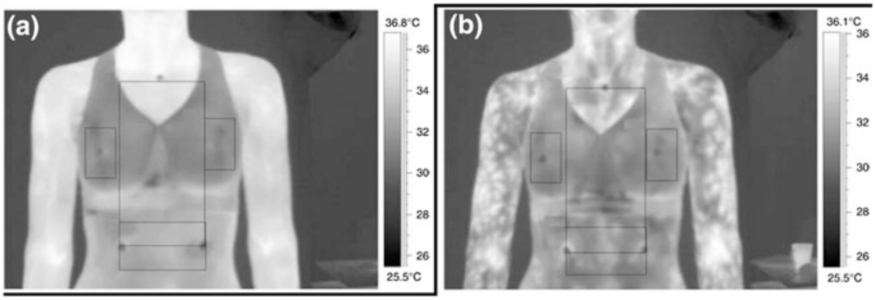

Fig. 7.5 Thermograms of bra and skin temperatures of a participant wearing the composite bra before (**a**) and after (**b**) exercise in the thermoneutral condition. Regions of interest are highlighted. Figure obtained from Ayres et al. [64]

than in the composite bra. There was yet no significant correlation between thermal comfort and pre-post skin temperatures with large variability in comfort responses. Ayres et al. [64] also pointed out that both bras displayed a similar shape and coverage. Nevertheless, there was a mesh section in the composite bra at the back and this corresponded approximately to an open uncovered section in the polyester bra.

Several future directions in bra ergonomics were suggested with the influence of additional clothing layers, the contribution of other physiological factors (hydration, heart rate, core temperature) on breast thermal comfort. The results also highlighted the importance of optimising the design of sports bras in order to facilitate the cooling ability of the skin. These changes can improve thermal comfort which may also lead to differences in athletic performance [64].

7.3.3 Assessment of Hiking Ensembles

Hiking is a popular recreational activity with large participant numbers varying widely in terms of age, gender and hiking experience [65]. In severe cases, hypothermia can occur during hill walking and this has been associated with reduced clothing insulation (cold, wet and windy weather) and progressive fatigue due to the inability to compensate heat loss with heat production [66–68]. Adequate clothing ensemble is therefore required in changing outdoor settings (water repellent, minimal condensation) along with good pacing strategy to allow for sufficient energy expenditure. Apart from Pugh [69], no studies have assessed body temperatures and associated thermal comfort of hikers facing non-adverse conditions. Fournet et al. [70] replicated the thermal strain of a normal day hike in cool conditions within the laboratory and integrated infrared thermography to assess skin temperatures under clothing over the whole-body at different stages.

Eight males and eight females performed a simulated morning walk 2*30 min of uphill walking (15% gradient) at 55% VO_{2max} followed by 15 min seated rest at the top (with 10 km h^{-1} wind) followed by 30 min of downhill walking (15% gradient) at 20% VO_{2max} [70]. In the first half of the ascent, participants were wearing trousers (Forclaz 900, Quechua, Decathlon, France), T-shirts (Forclaz Quechua, Decathlon, France), fleece (Florclaz 50, Quechua, Decathlon, France), sports bra for females (Sportance, Kalenji, Decathlon, France) as well as backpack with 10% body mass (Forclaz 50L, Quechua, Decathlon, France). In the second phase of the ascent, they removed the fleece layer. Environmental conditions were changed from 5 °C, 50% rh to 15 °C 60% rh during the first 30 min to mimic real life conditions in a condensed manner.

Mean skin temperature was significantly lower for females compared to males (−0.7 °C) during the uphill and resting stages [70]. Locally, skin temperature changes were more pronounced in females compared to males, except for the legs. Notably, anterior arm skin temperatures fell by 3 °C during the uphill phase in females and by 2 °C in males. Females had significantly colder thermal sensation at the start, a less humid wetness perception after 30 min of ascent, and they had larger thermal discomfort at rest when exposed to wind.

Group-averaged thermograms were obtained at each stage using the image processing method described by Fournet et al. [57]. The relative maps of skin temperature distribution enabled a direct comparison between males and females despite differences in mean skin temperature (Fig. 7.6).

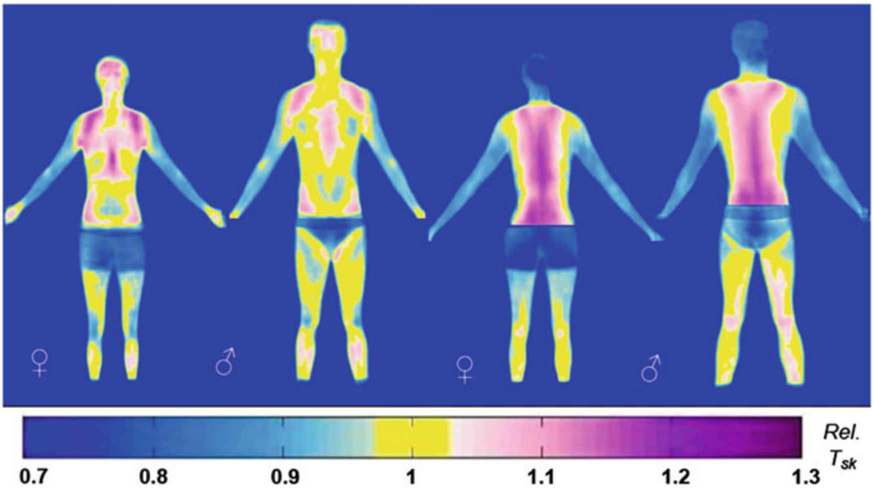

Fig. 7.6 Anterior (*left*) and posterior (*right*) group averaged relative whole-body maps of skin temperature for females (♀) and males (♂) after 60 min of uphill walking at 55% VO_{2max} in a 15 °C, 60% rh environment with uniform clothing insulation. Thermograms are normalised to mean skin temperature, with a value of 1 equal to mean skin temperature in both groups. For example, 0.7 corresponds to 0.7 times mean skin temperature. Figure adapted from Fournet thesis [51]

Patterns of skin temperature distribution were highly similar between males and females. This is in line with a study on unclothed male and female runners [3]. Interestingly, no correlation of the temperature distribution with local skinfold thickness was observed suggesting that other factors than fat distribution are responsible for the skin temperature distribution.

Main consistencies in the thermal patterns were related to the warmer upper body versus lower body, a V or Y shape of warmer skin temperature over the anterior torso, the warmer lower leg over active muscles, the colder arms due to the absence of clothing insulation (short sleeve T-shirt during the second ascent phase). The influence of the backpack was clearly noticeable with higher skin temperatures in localised body regions in contact with the shoulder straps, the belt (with abdominal pads) and the upper/lower back which seemed more pronounced in females (Fig. 7.6).

Interestingly, males performed an additional trial without backpack at a similar heat production. The quantitative analysis (based on specific control points) highlighted the magnitude of these local effects reaching a maximum of 3 °C higher skin temperatures in the lower back for the backpack condition [51].

The use of infrared thermography for the assessment of sport garments described in the literature remains limited to a few number of studies. In certain thermo-physiological studies where rapid temperature changes are expected, it seems inadequate unless the area of interest is not located under clothing. On the other hand, infrared thermography and specific processing methods can help in the evaluation of clothing interventions such as warming or cooling jackets [48, 71], different garment composition [4, 64], the addition or subtraction of clothing layers [51, 61] or other sport equipments [51, 72]. The main advantage of mapping large body surfaces is rarely exploited as quantitative analysis are often limited to defined regions of interest (e.g. Ayres et al. [64]) not necessarily taking into account the natural pattern of skin temperature distribution. The understanding of these patterns in connection with clothing properties, the type of sport and external determinants (e.g. wind) can be extremely useful to better adapt the design, the choice of material of sport garments using a bodymapping approach for improved thermal comfort and exercise performance.

7.4 Infrared Thermography and Bodymapping Sport Garments

7.4.1 Design and Evaluation of Bodymapping Garments

A bodymapping approach refers to the knowledge of biological and/or sensorial responses associated with several body regions exposed to the same stimulus or condition. Havenith et al. [1] exposed the principles of this bodymapping approach in the field of thermal comfort and clothing ergonomics. Regional clothing adaptation can be made according to the regional knowledge of skin temperature, sweat production/skin wettedness and the regional skin sensitivities to temperature and wettedness [1]. Many bodymapping studies on these parameters have been performed using different techniques, with local thermal stimulations [73–76], local sweat collections with absorbent pads [1, 77, 78], simultaneous contact sensors [30, 79] and infrared thermography for skin temperature mapping [3, 51, 57, 70].

The combination of the different maps and their relevance according to the exercise type and environmental conditions is determinant for clothing manufacturers. This may lead to improved thermal-wet perceptions, more efficient heat loss or preservation, reduced sweat loss that can all contribute to exercise performance.

Wu et al. [80] attempted to use this kind of approach by combining skin temperatures and several thermal-wet perceptions in connection with the evaluation of 10 kinds of hygroscopic fibres. They developed a T-shirt assembled with 4 fabrics matching regional requirements.

The choice and position of fabrics can be based on various bodymaps. Yet, in the overall garment construction, garment fit plays a crucial role by modifying the heat and mass transfers between the skin and environment. Some studies have therefore performed quantification of the volume and size of air gaps determined by garment fit [81–83]. They have highlighted the uneven distribution of air gaps layers using 3D body scanners. Zhang et al. [83] combined this assessment with infrared thermography of clothing surface temperatures [83] (Fig. 7.7).

They found that air gap usually have larger thickness in concave areas (lumbar region) and smaller thickness in convex areas (hips, shoulders) formed by the human skeleton and muscles. Clothing surface temperature decreases with increasing air gap thickness up to a critical thickness of 15 mm upon which natural convection occurs [83]. Based on this local knowledge, a revised pattern was designed with additional cover cloth on the shoulder and waist darts in the back waist region. This led to an improved thermal insulation of the new garment as measured on a thermal manikin.

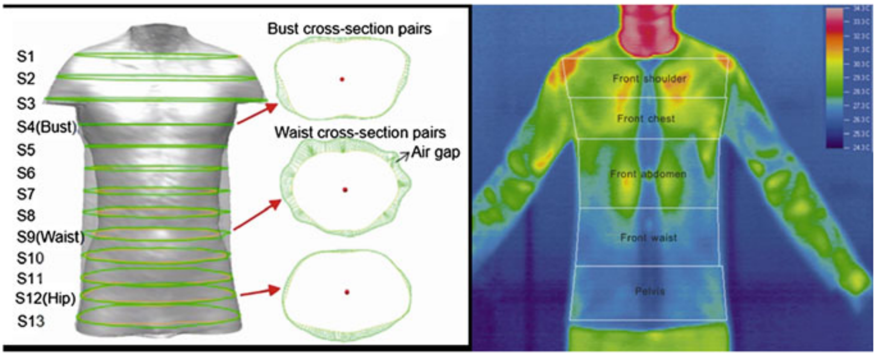

Fig. 7.7 3D scanner analysis with the selection of cross section pairs (*left*) and clothing surface temperatures (*right*) with regions of interest for the same garment. Figure obtained from Zhang et al. [83]

In the five-level system for the analysis of the physiological properties of textiles and garments [84], manikin testing represents a key level in the assessment of sportswear. It provides overall heat and vapour resistances as well as localised resistances depending on the number of body segments. Kicklighter et al. [85] reported that the scientific knowledge on bodymapping sportswear engineering has lagged far behind commercial practices of these garments.

A few studies have analysed the thermal properties of bodymapping sportswear on sweating manikins [17, 86, 87] as well as their implications for physiological and perceptual responses through human testing [3, 17, 80, 83].

The presence of mesh or openings at the two vertical side seams was found to be ideal for ventilative cooling based on manikin testing in a constant temperature mode [17, 86]. Wang et al. [87] used a manikin in thermoregulatory mode and demonstrated that bodymapping sportswear did not provide global advantages (mean skin and core temperature) but local improvements in heat and vapour transfer were beneficial for local thermal perceptions, especially with a modular system.

Wu et al. [80] measured lower thermal and sticky sensations using a bodymapping T-shirt with 25 females at very low exercise levels in a 24 °C 55% rh environment. Zhang and Li [17] observed lower skin temperatures with mesh fabrics at the front torso (vertical) for 6 males running at 40% $VO_{2\max}$ in a 25 °C, 50% rh environment. There were no differences in perceptual responses between all bodymapping garments varying in mesh location but thermal comfort was significantly improved compared to a no-mesh control condition [17]. Lastly, Wang et al. [83] reported significantly improved physiological responses (lower mean skin and core temperature, mean torso temperature and heart rate) and local thermal sensations with a modular tight-fitting bodymapping kit worn by 8 males running at 10 km h^{-1} in a 30 °C 40% rh environment.

In warm to hot environment, these bodymapping studies focused on adapting the wicking, air permeability and vapour resistance of fabrics assembled in sport garments mainly based on knowledge of sweat production and efficient garment construction. Skin temperatures were measured by local contact sensors potentially over-estimating or under-estimating the impact of specific fabrics locally [42]. Infrared thermography could bring more insights into the real efficiency of bodymapping sport garments and provide directions into improving their benefits for thermal comfort and exercise performance.

7.4.2 *From Thermograms to Bodymapping Garments*

Infrared thermography can be used for whole-body temperature mapping [2, 3, 51, 57, 70] and this knowledge can be translated into bodymapping sportswear. Havenith et al. [1] suggested that placing extra insulation on the specific cold body regions would be beneficial for overall thermal comfort whilst targeting the warm regions could prevent unwanted heat loss. The natural whole-body distribution of temperature is required for this kind of strategy towards improved garment, especially for cold weather sports or activities. Furthermore, this distribution can also serve in the heat to maximise heat loss or for targeted cooling interventions, though regional skin temperatures become almost similar above 30 °C air temperature during exercise [88].

Domina et al. [89] described a method based on 3D scanning and infrared thermography in order to provide individual thermal profiles. Image registration techniques are used to transform 2D thermograms onto 3D scans of the same person (Fig. 7.8). They suggested that this could lead to bodymapping garments customized by function (heat dissipation or preservation) and by fit necessary for designers and product developers. Domina et al. [89] mentioned potential improvements in performance as well as cost savings due to more specific placing of fabrics or finishes. Preliminary results using this method (bodymapping garment designed for the upper body) were promising for improved thermal comfort and reduced skin temperature changes during a short duration exercise (Harvard Step test) on 2 males in a 2 °C but not in a 29 °C environment [90].

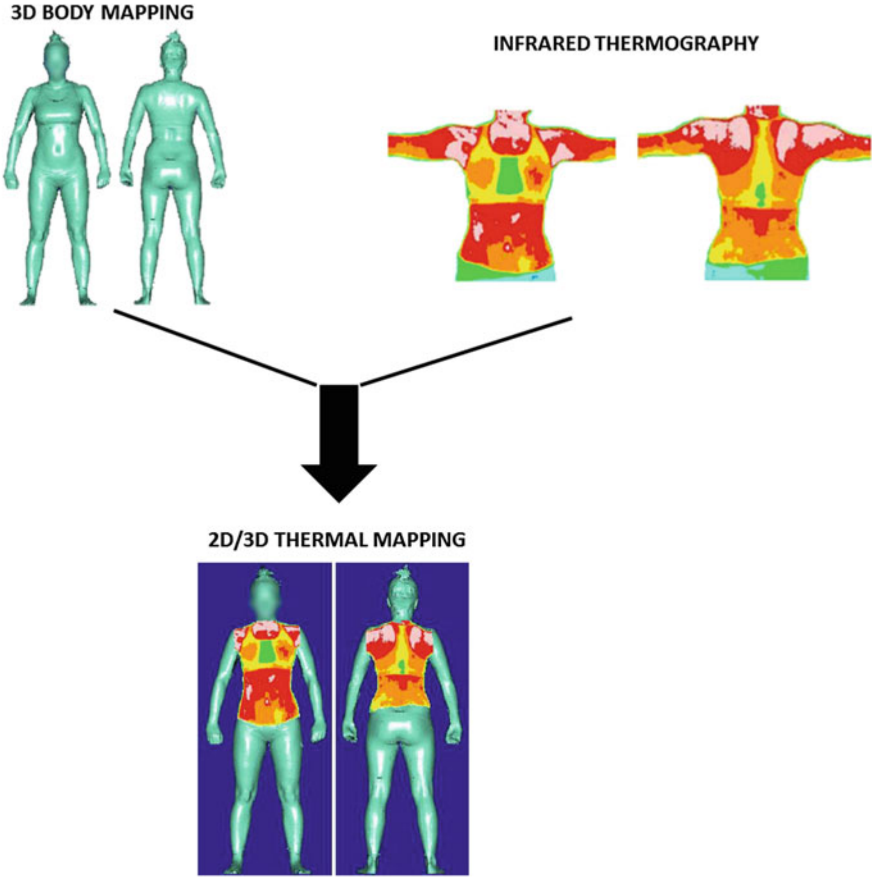

Fig. 7.8 2D/3D thermal mapping method described in the study of Domina et al. [89]. Figure adapted from Domina et al. [89]

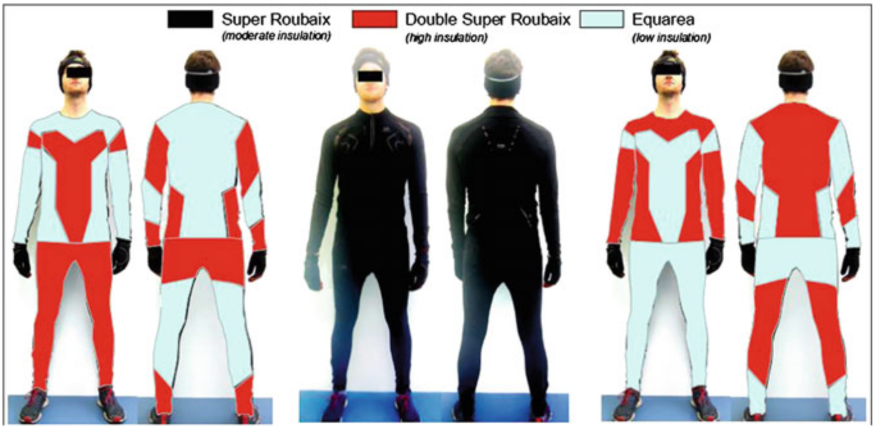

Fig. 7.9 Presentation of the 3 clothing ensembles (C, U and W). Normal colour was black for all ensembles. Figure adapted from Fournet thesis [51]

Fournet et al. [2] investigated for the first time the suggestion by Havenith et al. [1]. Bodymapping sport garments were designed based on the natural distribution of skin temperature distribution under clothing obtained by infrared thermography whilst running in the cold (see Fig. 7.3). Thermal patterns were divided into 2 isotherms of skin temperatures to decide about the body regions where clothing insulation was modified. Two levels of insulation (high and low) were applied within the running ensemble and compared to an ensemble where moderate insulation was uniformly distributed (Clothing U). Clothing C was designed to add insulation in the naturally cold regions, Clothing W in the naturally warm regions (Fig. 7.9). All clothing ensembles had similar overall clothing insulation (0.7 Clo).

Twelve males performed a 40-min running bout at 70% VO_{2max} in a 5 °C, 50% rh environment. Overall thermoregulatory responses were not affected by the type of clothing (similar mean skin and core temperature). Regional skin temperatures assessed by infrared thermography were strongly affected due to the different distributions of insulation. Clothing U led to a natural skin temperature distribution whereas Clothing W reinforced this distribution and Clothing C significantly reduced skin temperature variations across the whole body (creating a more homogenous pattern). High insulation induced 2–2.5 °C higher regional skin temperatures compared to thinly insulated condition irrespective of placing the insulation on naturally “warm” or “cold” regions (Fig. 7.10). High insulation in W had a significant negative impact on thermal comfort in the upper back and arms as they were perceived warmer and wetter compared to clothing C and U. Overall, there were more positive comfort ratings for C suggesting the benefits of reducing skin temperature contrasts between regions [2].

Further studies are required to understand the influence of bodymapping sportswear in the cold. Manipulation of local heat resistances could be mixed with the manipulation of vapour resistances to maximise comfort and performance in

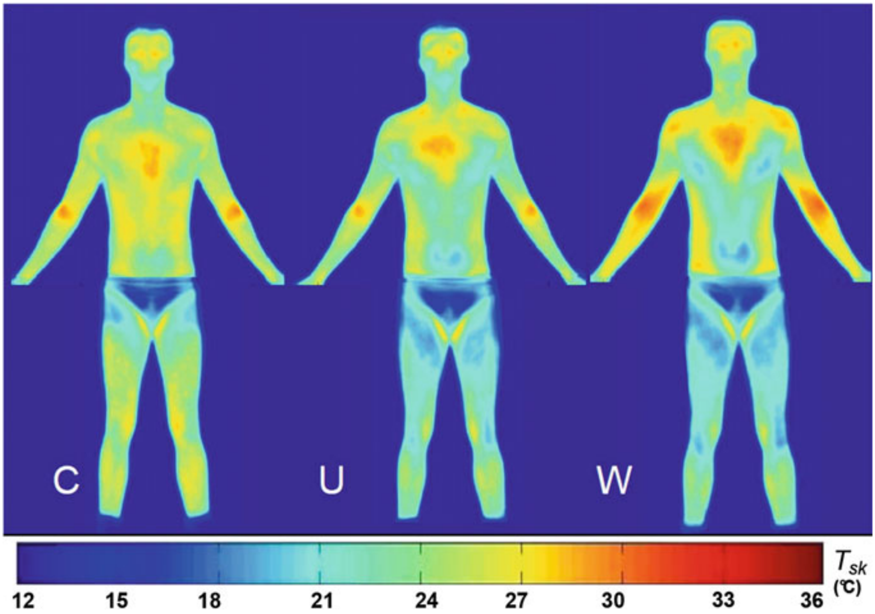

Fig. 7.10 Anterior group-averaged whole body maps of skin temperature for clothing C (covering the cold regions), clothing U (uniform moderate insulation) and clothing W (covering the warm regions) for 12 males after 40 min of running at 70% VO_{2max} in a 5 °C environment. Figure adapted from Fournet thesis [51]

moderate to high intensity exercise where sweat production and skin wettedness can be detrimental [6]. Fournet [51] also presented modular systems allowing easy and quick behavioural adjustments of the local heat loss by the wearer to take into account the wide variety of weather conditions (especially in outdoor sports) and the potential variations in exercise intensity due to pacing or the sport demand.

Infrared thermography was the perfect tool to assess the efficiency of the clothing intervention and can be promising in both evaluating normal patterns and deviations from these patterns with bodymapping sportswear [2].

7.5 Conclusion

Infrared thermography has been used only to a small extent in the field of sportswear ergonomics. There are yet numerous examples where this method could be used in addition to contact sensors for the measurement of skin temperatures. Some challenges need to be overcome regarding processing time, method and speed of clothing removal as well as standardised processing techniques for the analysis of thermograms. Nevertheless, the individual qualitative and quantitative information obtained by infrared thermography can be extremely valuable to assess the efficiency of sports garments at the skin interface (warming, cooling, reducing temperature contrasts), consequently leading to improvements in thermal comfort and/or exercise performance.

Athletes or coaches may benefit from the development of external device (such as drones with integrated infrared cameras) able to monitor the uncovered body part (hands and face) of sporting situations in order to track/predict emotional and physiological changes [91]. With increasing wearable sensors integrated into clothing, one can imagine sport garments that could automatically adapt to these changes taking also into account weather conditions, heat production and the skin temperature/wettedness.

Infrared thermography can also help in the development of more customized sport garments where individual temperature patterns can be useful for targeted heat loss or preservation. High resolution thermograms can display the exact positions and variations of muscle perforators where substantial heat is being released. Favouring the extraction of heat or cooling intensely these spots may prove beneficial for temperature regulation.

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