Institution: Loughborough University		
Unit of Assessment: UOA32 - Art and Design: History, Practice and Theory		
Title of case study: Protecting the person: Optimising thermal safety, effectiveness and comfort of work, clothing and built environments		
Period when the underpinning research was undertaken: 2002-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof George Havenith	Professor of Environmental Physiology and Ergonomics, Director EERC	1998 to present
Dr Simon Hodder,	Senior Lecturer	2007 to present
Dr Davide Filingeri,	Lecturer	2016 to present
Dr Alex Lloyd	Lecturer	2016 to present;
Period when the claimed impact occurred: 2014-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Organisations and manufacturers need to better understand the impact of thermal stress on the safety and comfort of their employees and consumers, from life-critical situations to user experience and product desirability. Research at Loughborough University on human perceptual, psychological, and physiological responses to temperature stress led to four key impacts: 1) **Prevented heat-related deaths** in the UK Army; 2) **Improved economic competitiveness** of Computational Fluid Dynamics (CFD) software, used for design of more thermally comfortable cars, clothing and buildings; 3) **Improved applicability and extended global reach** (outside Europe and USA) of the most used indoor-climate design and evaluation standard (ASHRAE 55), and 4) Global sports brands ([text removed for publication]) adopted evidence-based clothing design, leading to **innovative products and improved brand competitiveness.**

2. Underpinning research

Research at Loughborough's Environmental Ergonomics Research Centre (EERC) by Professor Havenith and Drs Filingeri, Hodder, and Lloyd has considered a range of perceptual, psychological, and physiological responses to temperature stress. Part of the research focussed on athletes/workers/soldiers exposed to extreme heat. Knowledge on this topic was built up through MOD and EU funded projects (G6RD-CT-2002-00846; FP7-229042; Horizon 2020 R&I-668786; EU-COST action 730) looking at the safety of soldiers and workers avoiding heat illness in hot workplaces. Starting from our simulation models for work/exercises in the heat **[R1]**, we added research on the impact of protective clothing and the development and measurement of body temperature in extreme conditions **[R2]**. Our latest simulation model allowed the conditions of military exercises where deaths occurred to be analysed and the underlying causes identified.

Clothing insulation data of garments different from the standard western dress (e.g., African, East Asian, Arabic and South Asian) were measured and published **[R5]** enabling the expansion of the database on clothing insulation data to be used as input into the ASHRAE (American Society for Heating Refrigeration & Air-conditioning Engineers) and ISO building climate design and evaluation standards. This was funded through two specific competitive research calls by ASHRAE (£350k).

A third research area focussed on understanding more general temperature regulation processes, how these are differentiated between different body areas (body mapping), how they vary between different populations (male/female, lean/obese, healthy/MS patients etc.), how they interact with clothing and how they relate to thermal comfort or discomfort **[R3, R4, R6, R7]**. Building on our research creating maps of sweat distribution across the body (e.g., Figure 1), showing important differences in sweating responses between men and women relevant to clothing design **[R3]**, our body mapping work continued. We determined differences in sweat production and skin temperature development across the body between unfit and fit individuals, differences in pre-pubertal children (under-developed sweat system)

and in the elderly (changed distribution and reduced sweat sensitivity) and important changes as a consequence of heat acclimatisation (improved sweat distribution leading to optimised heat loss). Apart from improving our general understanding of thermoregulation, these data are all crucial to optimising clothing fabric selection and clothing design for these specific population groups.

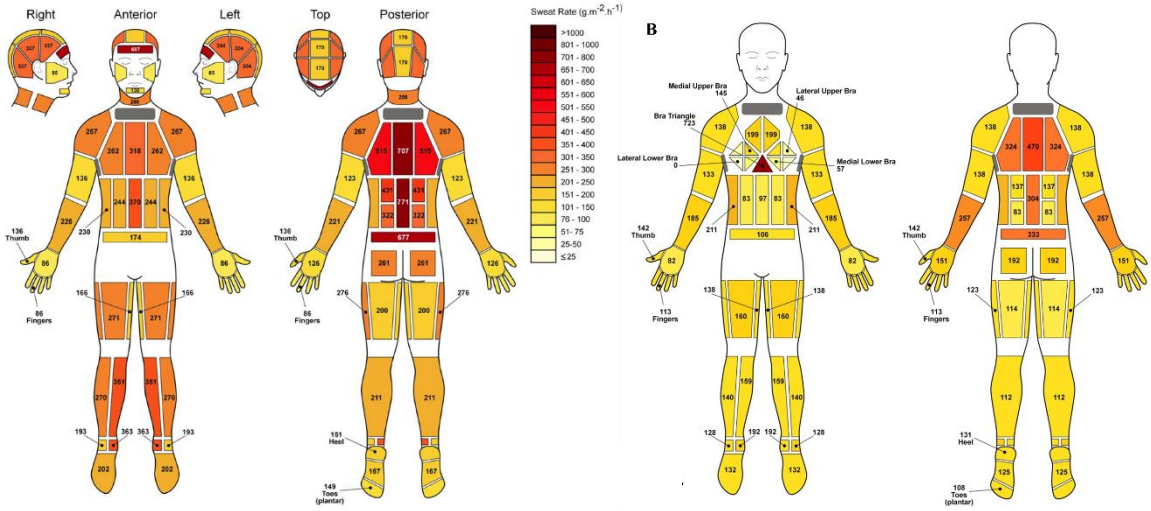

Figure 1: Example of body mapping research (R3): sweat map of male (left) and female (right) athletes during exercise. Darker colours showing higher sweat rates. Data used to inform selection of clothing fabrics for different body sections related to moisture absorption and wicking capacity.

Our novel work on mechanisms and distribution across the body of cold and warmth sensitivity and of wetness perception **[R4]** also demonstrated significant variation across the body, relevant to the optimal design of garments including placement of ventilation openings, distribution of thermal insulation and choice of contact textile. We went on to focus on the sensory interaction with textiles and with footwear **[R6]**, answering the issue of how big improvements in the product specifications must be before the wearer can notice a significant difference in product performance. Finally, we continued a detailed investigation of sweat gland function. This all provided building blocks for human thermal simulation models and for evidence-based design of improved clothing and footwear**.**

3. References to the research

R1: Havenith G, Fiala D (2016) Thermal Indices and Thermophysiological Modeling for Heat Stress. Comprehensive Physiology, 6: 255-302. https://doi.org/10.1002/cphy.c140051

R2: Richmond V L, Davey S, Griggs K, Havenith G (2015) Prediction of core body temperature from multiple variables. Annals of occupational hygiene, 59(9), 1168-1178. https://doi.org/10.1093/annhyg/mev054

R3: Smith CJ, Havenith G (2012) Body mapping of sweating patterns in athletes: a sex comparison. Medicine & Science in Sports & Exercise, 44(12), 2350-2361. DOI: https://doi.org/10.1249/mss.0b013e318267b0c4

R4: Filingeri D, Fournet D, Hodder S, Havenith G (2014) Body mapping of cutaneous wetness perception across the human torso during thermo-neutral and warm environmental exposures. Journal of Applied Physiology, 117(8), 887-897. https://doi.org/10.1152/japplphysiol.00535.2014

R5: Havenith G, Kuklane K, Fan J, Hodder S, Ouzzahra Y, Lundgren K, Au Y, Loveday D (2015) A database of static clothing thermal insulation and vapor permeability values of non-Western ensembles for use in ASHRAE standard 55, ISO 7730, and ISO 9920. ASHRAE Trans, 121(1), pp.197-215. http://www.techstreet.com/ashrae/products/1894263

R6: West AM, Oberst F, Tarrier J, Heyde C, Schlarb H, Brüggemann GP, Hodder S, Havenith G, (2020) A thermal foot manikin as a tool for footwear evaluation and development. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering & Technology, online: September 2020. https://doi.org/10.1177%2F1754337120952229

R7: Raccuglia, M., Lloyd, A., Filingeri, D., Faulkner, S. H., Hodder, S., & Havenith, G. (2016). Post-warm-up muscle temperature maintenance: blood flow contribution and external heating optimisation. European journal of applied physiology, 116(2), 395-404. https://doi.org/10.1007/s00421-015-3294-6

The research was funded by competitively-awarded grants from industry (R3, R4, R6, R7), the American Society for Heating Refrigerating and Air-conditioning Engineers (ASHRAE) (R5) and the EU (R1, R2) (>£3 million) and published in leading, peer reviewed journals.

4. Details of the impact

The Loughborough Environmental Ergonomics Research Centre's (EERC) research on human interaction with the thermal environment generated a broad range of insights related to thermal working conditions and risks, thermal physiological function, athlete performance and worker/athlete-clothing interactions leading to the following impacts:

Impact 1: Prevented heat-related deaths in the UK Army.

Our investigations underpinned new UK MoD/Army regulations to prevent heat-related deaths among British soldiers. On average, eight UK soldiers die annually during training exercises. Some die from excessive body temperature and many suffer from the lasting effects of heat illness. In 2013, soldiers Edward Maher, James Dunsby and Craig Roberts died in an SAS selection exercise and in 2016 Joshua Hoole died in an Army Fitness Test. Many more suffered from heat illness with lasting effects. Using our research **[R1, R2]** and expertise in the physiology and assessment of heat exposure, we provided expert witness evidence to the Crown Prosecution Services (2014), The Military Court (2018), Military Police (2019), HM Senior Coroner for North London (2018) and HM Senior Coroner for Birmingham and Solihull Districts (2015, 2019).

Our analysis of the 2013 soldiers' deaths due to heat illness, contributed to a *'Regulation 28 report to prevent future deaths'* in 2015 by the Coroner for Birmingham and Solihull, which drew on the failures we identified in the protection procedures of soldiers during the exercise. With the 2016 death of Joshua Hoole, our investigation refuted an Army report claiming no heat stress limits were breached. Our research showed that formal safety limits for the exercise were exceeded, which went unrecognised due to procedural mistakes in the use of the assessment equipment. HM Coroner, based on our report, immediately submitted a further *'Regulation 28 report to prevent future deaths'* **[S1]** to prevent the risk of re-occurrence. The then Secretary of State for Defence (Gavin Williamson) **[S2]** actioned several measures, citing our report, including warning/instruction labels to be put on all heat stress monitors in use nationally and internationally by the Army to ensure earlier mistakes would not be repeated.

Impact 2: Improved economic competitiveness of Computational Fluid Dynamics (CFD) software, used for design of more thermally comfortable vehicles, clothing and buildings.

In the design of building and vehicle climate systems, traditionally, the focus has been on simulation of the physical heat exchange processes of the vehicle/building with the environment using extensive (CFD) computer models. The translation to driver/worker comfort in the past was over-simplified. Our research **[R3, R4, R6]** was used by [text removed for publication], a leading global company in specialist thermal modelling, to develop a virtual Human Thermal Model (HTM) extension to existing CFD (vehicle/building) models to evaluate the impact of the environment in vehicles, buildings and spacecraft on human comfort and thermal perception. Our detailed sweat, temperature and sensitivity distribution maps for

different populations, for the first time, allowed this virtual human to be set to respond as male, female, fit, unfit, obese, lean, old, young, Asian, European, etc. as required for individual customers.

For [text removed for publication], their Chief Technology Officer wrote about EERC impact: *"for the continued development of our model, we have relied on your publications on sweat distribution"* **[R1]**; *"Of particular interest to our automotive customers is your research on thermal perception differences between East Asian populations and Westerners".* He confirmed that EERC research *"has been invaluable in broadening our understanding of basic thermo-physiological mechanisms, heat and moisture transfer in clothing, and comfort perception".* [text removed for publication] integrated our ongoing research into the models leading to a better product and economic benefit for the company **[S3]**. The model generates *"sales of over $1 million annually"* and has relied substantially on research by EERC: *"Your contributions are significant given the widespread international use of our human thermoregulation model, by academia, government and industry, including automotive OEMs, architectural firms, defence organizations and clothing/PPE designers, who need to simulate humans for various applications, including comfort, effectiveness, and safety".* The model's use *"has improved the health and wellbeing of people".*

Impact 3: Improved applicability and extended global reach (outside Europe and USA) of the most used indoor-climate design and evaluation standard (ASHRAE 55).

Our research **[S4]** addressed a need identified by the American Society for Heating Refrigeration & Air-conditioning Engineers (ASHRAE, 57,000 members worldwide) to make its indoor climate comfort standard (ASHRAE 55) usable more widely across the globe. This was achieved by providing engineers with input data specific for non-western (beyond the US and Europe) countries, where clothing and dressing behaviour differs from the standard western office attire, for which the standard originally was designed. EERC produced extensive tables with insulation and vapour resistance values of African, East Asian, Arabic and South Asian clothing, published as an ASHRAE report (TRP1504) and journal paper of which a selection was embedded in the latest (2019) instructions for the use of Standard 55. The new guidance delivered the tools to apply the standard in other continents (beyond the US and Europe) with very different clothing behaviour. This substantially expanded the application range and reach of the standard, transforming it into a truly global standard and enabling thermal engineers to use it worldwide.

Impact 4: Global sports brands adopted evidence-based clothing design leading to innovative products and improved brand competitiveness.

Sporting clothes brands need to "*innovate continually to improve athlete performance, material function and wearer comfort, to remain competitive as a brand"* **[S6]**. Our industry-funded research **[R3, R4, R6, R7]** created economic impact by enabling three global companies [text removed for publication], [text removed for publication] and [text removed for publication]**,** all with extensive clothing R&D departments, to develop better, innovative products with features that are attractive to consumers, along with better communication of the functionality of these features **[S5-S7]**. Key impacts that are stated by these manufacturers are that, by using our research, they:

1: developed better performing, innovative products.
2: increased user comfort and performance.
3: improved the communication of product features to the consumer.
4: improved internal testing procedures during product development.

a) For [text removed for publication], the Senior Manager for Sport Science at '[text removed for publication] confirmed that the expertise provided by our research enabled the company to "*match the right functionality of a new technology to the actual athlete needs"* and as such, *"the thermophysiological expertise provided by EERC is crucial for adidas"* **[S6]**. He further reported that "*Body maps of athlete's sweat production zones* **[R3]** *have made a tremendous*

contribution to [text removed for publication] *understanding of human performance and enabled adidas to design better performing apparel sold globally".*
[text removed for publication] were also able to use our research to develop clothing specifically for children: "*recent body heat mapping research in pre- and post-pubertal children has shown strongly deviating heat maps from adults, culminating in innovative sports garments developed specifically for this age group."*

In relation to EERC's research on thermoregulation and comfort in footwear, he stated: *"The results on thermal sensitivity and wetness perception in athletic footwear* **[R6]** *gave our engineering team an indication about how much change in a construction is required to have a perceivable impact on the athlete before and during exercise",* which "*had immediate impact on our internal testing procedures".*

b) For [text removed for publication]**,** the Principal Researcher, Applied Apparel Research, expressed the impact of EERC research for the company's design process as: *"The knowledge generated by your team…has helped us generate 3D digital avatars of the athlete body that … drive product design seamlessly".* Regarding new products*,* he confirmed that our results *"are helping us in the design of innovative products mapped around the body's skin sensitivity* **[R4]**, *in order to maximize athletes' comfort and performance"* **[R7].** Regarding improved communication of benefits to the user/buyer he stated that EERC research *"helped us communicate the benefits of our innovative products to athletes and consumers"* **[S7]**.

c) For [text removed for publication]**,** the R&D project manager confirmed the use of our research in [text removed for publication] product development: *"In the last 7 years, the body mapping knowledge provided by the EERC research* **[R3, R4]** *was successfully integrated in our heated garments line (hiking and ski jackets, running vests), actively ventilated skiing jackets and variable (inflatable) insulation jackets".*

Regarding consumer communication improvements, he stated: *"Research on pre-pubescent children helped the creation of the first sensorial models adapted to exercising children in the cold, allowing* [text removed for publication] *to give evidence-based customer/parent recommendations on indicative comfort temperatures for clothing as a function of their thermal resistances (from 2019 onwards).".* He described the impact for [text removed for publication] as "*very large as this concerns most of our children product ranges (jackets and pants) for the winter season, with for example hiking, skiing and horse-riding products"* **[S5]**.

5. Sources to corroborate the impact

S1: REGULATION 28 REPORT TO PREVENT FUTURE DEATHS - Coroner's report to secretary of State for Defence
Report of Senior Coroner for Birmingham & Solihull to the Secretary of State for Defence and the Ministry of Defence, referring to the report provided by Professor Havenith, in advance of the inquest into the death of Joshua Hoole. "CORONER'S CONCERNS: During the course of the investigation, an expert report has revealed matters giving rise to concern. In my opinion there is a risk that future deaths will occur unless action is taken. In the circumstances it is my statutory duty to report to you." The issue refers to an incorrect use of the heat stress assessment instrument, which was identified in the Loughborough University report.

S2: Letter from secretary of state THE RT HON GAVIN WILLIAMSON CBE MP
This letter cites the expert witness report by Prof Havenith for the Birmingham Coroner and indicates actions taken by the MOD in response to one of the shortcomings listed in the report.

S3: Letter from [text removed for publication] **about impact (confidential)**

S4: Copy of guidance for use of ASHRAE standard 55, published in ASHRAE handbook, chapter 9, see table 8.8 and related text.

S5: Letter from [text removed for publication] **about impact (confidential)**.

S6: Letter from [text removed for publication] **about impact (confidential)**

S7: Letter from [text removed for publication] **about impact (confidential)**