**Institution: Loughborough University**

**Unit of Assessment: D34 Art and Design, History, Practice and Theory**

**Title of case study: Improved athletic performance and sports clothing design through the provision of environmental ergonomics and physiology based design guidelines**

## 1. Summary of the impact

Clothing companies have introduced the 'body mapping' design guidance developed in the Environmental Ergonomics Research Centre into many of their clothing lines (2007-2013) as Unique Selling Points, enhancing comfort and functionality. The most recent major impact (2009-2012) is the development and evaluation of specialised heated trousers ('British Cycling hotpants') that were used by the Olympic track cycling team to maintain their muscle temperature between warm-up and race, contributing to the medal success of Team GB. Understanding of body sweat distribution also improved computer models used to assess health and safety for workers exposed to heat stress, and has fed in to thermal manikin design. The main impacts are on 'economy' (sales), 'performance', and 'understanding'.

## 2. Underpinning research

Researchers at Loughborough University: Prof. G. Havenith, 1998-current.; Dr. S. Hodder, 2007-current.; 3 RA's, 2002-2012; 7 PhD students, 2002-2013.

This area of (mostly CONFIDENTIAL) interdisciplinary work (linking sports science, ergonomics, textile science and design of sport and protective clothing) developed from the long term (>10 years) collaboration of Prof Havenith with sporting goods companies [text removed for publication], and with the MOD. Initially funded in small projects through the enterprise route, a larger MOD project (**G3.1,** DSTL, 2003-2005) and two EU project (**G3.2,** 2002-2005; G6RD-CT-2002-00846; **G3.7**; FP7-229042 Protective Responsive Outer Shell) laid the groundwork in this area of research on heat transfer from the body through clothing. This was followed by a series of international cooperations, enterprise projects and PhD projects. Most projects were funded by [text removed for publication] (**G3.4, G3.5**; 3 PhD's; 2006-2016 + enterprise) and by [text removed for publication] (**G3.3, G3.6**; 4 PhD's; 2008-2014 + enterprise) (each PhD project in a different sub-area). These studies focussed on various different aspects of **body mapping**, i.e. research on the heat transfer from different body regions to the environment through clothing ventilation and evaporation (sweat distribution; **3.2**), the effect of moisture condensation in clothing **[3.6]**, and the effect on thermal sensation (moisture and temperature perception; **3.3, 3.4**) and on performance (Workers; **3.5**, Olympic athletes; **3.1**).

Based on these projects, the knowledge transfer consisted of providing design guidelines (body maps of sweating distribution and of thermal sensitivity) to the participating companies. These maps (**3.2, 3.3** and 2 other more recent publications) depict the distribution of sweat production over the body (top and recreational athletes; male and female athletes) and of thermal sensitivity providing guidance on where in the sports clothing to introduce more absorbing fabrics, extra ventilation, or other design features; the distribution of thermal sensitivity over the body, providing guidance especially for winter sports clothing on where extra cooling/ventilation would have the biggest impact on comfort; and the interaction of sweat production and ventilation providing guidance on design of ventilation openings in clothing. The novel methods for obtaining these maps were developed by Prof. Havenith and co-workers and have since been taken up by many others in the scientific community (e.g. **5.5, 5.6**).

In an extension to the study of regional heat/sweat loss across the body, a number of studies were performed on optimisation of heat extraction from the body (active cooling) in different body areas, as well as heating the body in different areas. A special segmented water perfused suit (16 body sections) was developed that allowed the study of heat exchange in 16 individual skin sections (**G3.5**). This research formed the basis for the work on the design of heated trousers by [text removed for publication] to be used by the British Cyclists in the London Olympics. Based on the experience that often there are periods of up to 30 to 40 minutes between warm-up and race in many sports events, a number of studies were performed in which muscle temperature was

measured using a sensor inserted into different depths of the muscle to study the muscle cooling process. Having established that the drop in muscle temperature can be up to 2.5ºC within 30 minutes after the warm-up, different heating interventions were studied for their effect on muscle temperature and on athletic performance. These studies were used to advise [text removed for publication] on the design of the heated trousers worn by athletes to maintain muscle temperature between the warm-up and the actual event **[3.1]**. Most importantly the research, including measurements of deep muscle temperature and of athlete performance, provided the evidence that this intervention was highly effective in improving power output of the athlete (9% improvement in peak power in a sprint **[3.1]**).

**3. References to the research** (indicative maximum of six references)

After expiry of contractual CONFIDENTIALITY periods (2-4 years per project), the research was published in leading peer reviewed journals as well as presented at various conferences to achieve a broad dissemination.


**3.1.** **Faulkner, SH.;** Ferguson, RA.; **Gerrett, N;** Hupperets, M; **Hodder, SG.; Havenith, G**; Reducing Muscle Temperature Drop Post Warm-up Improves Sprint Cycling Performance. *Medicine and Science in Sports and Exercise* 45(2):359-365, Feb **2013**, DOI: 10.1249/MSS.0b013e31826fba7f [citations 4]

**3.2.** **Smith CJ, Havenith G**; Body mapping of sweating patterns in male athletes in mild exercise-induced hyperthermia, *European Journal of Applied Physiology* 111(7):1391-1404 01 Jul **2011**. DOI: 10.1007/s00421-010-1744-8 [citations 33]

**3.3.** **Ouzzahra Y, Havenith G**, Redortier B, Regional distribution of thermal sensitivity to cold at rest and during mild exercise in males, *Journal of Thermal Biology*, 37(7), 517-523, November **2012**. DOI: 10.1016/j.jtherbio.2012.06.003 [citations 2]

**3.4.** **Fukazawa T, Havenith G.** Differences in comfort perception in relation to local and whole body skin wettedness, *European Journal of Applied Physiology*. 106(1), 15-24. **2009** DOI: 10.1007/s00421-009-0983-z [citations 18]

**3.5.** **Dorman LE, Havenith G**. The effects of protective clothing on energy consumption during different activities. *European Journal of Applied Physiology*., 105(3), 463-70. **2009** DOI: 10.1007/s00421-008-0924-2 [citations 26]

**3.6.** **Havenith, G.,** Richards, M., **Wang, X**., Bröde, P., Candas, V., den Hartog, E, Holmér, I., Kuklane, K., Meinander, H. and Nocker, W. "Apparent latent heat of evaporation from clothing: attenuation and "heat pipe" effects", *Journal of Applied Physiology*, 104, 142 – 149, Jan **2008**; DOI:10.1152/japplphysiol.00612.2007. [citations 62]


**Quality indicators:** The interdisciplinary research with international leaders in the fields led to a number of publications of which 6 samples are listed above. All papers were published in rigorously peer reviewed journals which are ranked highly in their areas: Medicine and Science in Sports and Exercise, Journal of Applied Physiology, and European Journal of Applied Physiology (IF=4.4, 3.8 and 2.1, ranked 3$^{rd}$ and 6$^{th}$ and 18$^{th}$ out of 85 in sports science [ISI web of science]); Thermal Biology (IF=1.4, 51$^{st}$ of 146 in Zoology), Textile Research Journal (IF= 1.1; 3$^{rd}$ of 21 in materials science-textiles), International Journal for Clothing Science and Technology (IF=0.5,12$^{th}$ of 21 in materials science-textiles)). Citations received so far: 2 for **3.3** (2012), 4 for **3.1** (2013), 33 for **3.2**, 18 for **3.4;** 26 for **3.5** and 62 for **3.6**, giving an average of 24+ citations per paper or 8 citations per paper per year (Google Scholar, November 2013).

**Quality indicated through uptake by industry:** Research outcomes (body maps) have been incorporated by [text removed for publication] in their designs (see **5.1** and **5.2** in section 5) and by Computational Fluid Dynamics (CFD) software companies in their programmes (**5.4**). **3.1** was accepted as evidence for the design and use of special heated trousers by the British Olympic cycling team (**5.3**).

**Prizes:** PhD students working on these projects received best paper awards: C. Smith, International Conference on Environmental Ergonomics (ICEE), Boston, US, 2009; Y. Ouzzahra, ICEE, Nafplio, Greece, 2011; N. Gerrett, Oxylane Research Symposium, 2010 and 2011; D. Fournet, best poster prize, European Association of Thermology (EAT) Porto 2012, Portugal.

| | When | Grant reference and title | Collaborators | Researchers | Funder/Value |
|---|---|---|---|---|---|
| **G3.1** | 2003-2005 | Optimisation of clothing design; sweat mapping, comfort and ventilation | MOD-DSTL | GH, AF, BQ | MOD-DSTL; £208k |
| **G3.2** | 2002-2005 | G6RD-CT-2002-00846 Thermprotect – heat transfer in protective clothing | 6 EU partners | GH, XW, LD | EU framework 5; £120k |
| **G3.3** | 2008-2011 | The Physiological Basis for Clothing Comfort | [text removed for publication] | GH NG DF YO | [text removed for publication] |
| **G3.4** | 2006-2009 | Body Mapping of Sweating Distribution | [text removed for publication] | GH CS | [text removed for publication] |
| **G3.5** | 2006-2009 | Body Temperature Manipulation and Exercise Performance | [text removed for publication] | GH SF | [text removed for publication] |
| **G3.6** | 2011-2014 | Mapping of thermal needs of the human body | [text removed for publication] | GH DF | [text removed for publication] |
| **G3.7** | 2009-2012 | FP7-229042 Protective Responsive Outer Shell | 15 EU partners | GH SD | EU framework 7; £268k |

## 4. Details of the impact

This work has been used by several clothing companies to design clothing based on the zones of high and low sweat and heat loss and different thermal sensitivity **[5.1, 5.2]**. By doing this research on both males and females, gender specific body maps were produced and following from this gender specific clothing designs were produced by the companies.

“The body maps of sweat production zones have made a tremendous contribution to the company’s understanding of human performance and have enabled the company to design better performing apparel and to provide athletes with optimal climate solutions. The so-called sweat maps have been introduced into the company end of 2007 and have been used since. The [text removed for publication] body maps play an integral part during product creation, both within the company’s innovation team as well as in inline product creation teams.” **[5.1]**

One of the first developments based on such studies was the development of electrically heated trousers to maintain muscle temperature between athletes’ warm-up and actual event. It was found that electrically heated trousers, designed by [text removed for publication] based on our data, to deposit heat in specific muscle groups reduced the muscle cooling significantly, and led to a surprisingly high improvement in performance in subsequent sprint trials. Having established this benefit, these trousers were further developed by [text removed for publication], British Cycling (BC) and the Environmental Ergonomics Research Centre for the Olympic Cycling Track Team. The trousers were received enthusiastically by the athletes (e.g. Sir Chris Hoy, Victoria Pendleton and Laura Trott) and used extensively in the 2012 Olympics in which they are considered to have contributed to the British success by British Cycling **[5.3]**: Sir Chris Hoy **[5.3, 5.7]** said: “I have definitely been feeling the benefits of the ‘hot pants’. As soon as you take them off immediately before you do your standing start or flying effort, your legs feel like they are ready to go. You feel like you did at the end of a warm up but not out of breath or fatigued from it. It gets you in the optimum state for training and competition.” **[5.3]**; Matt Parker, Director of Marginal Gains, GB Cycling said: "The aim of the British Cycling marginal gains strategy is to develop a performance advantage through the application of cutting edge science and technology. What [text removed for publication] has delivered with the muscle warming

garment is a key component of our performance preparation". **[5.3]**

[Text removed for publication] launched the product during a special press event. Numerous reports were published worldwide **[5.7, 5.8, 5.9, 5.10]** and within the company it was judged as the most significant innovation for the London 2012 Olympics" **[5.1]**

As a second impact type **[5.4]**, these maps were also implemented by developers of computer models of human thermoregulation used in assessment of extreme environments and vehicle climate systems, and thirdly they are used in design of thermal manikins, used for testing and development of clothing and climate systems (e.g. cars), that artificially sweat. This sweating can now, based on this research, be regionally controlled/modelled rather than uniformly over the body, achieving a more realistic result:

"Since the recent release of RadTherm v10.2 [Heat Transfer Analysis Software for cars, aeroplanes etc.; http://www.thermoanalytics.com/products/radtherm], ThermoAnalytics has advanced beyond the capabilities of currently published thermoregulation models to provide a new segmental model of human thermoregulation that is consistently and accurately able to predict local and whole body thermo-physiological response in transient and asymmetric environments. This was accomplished in a large part due to recent research, such as the latest publications that you have co-authored with Smith (2011, 2012), which provided a fundamental key to the understanding of how sweat is distributed throughout the human body for both males and females". **[5.4]**

The novel methods developed by Prof. Havenith and co-workers and the results have since been taken up by many others in the scientific community (e.g. **5.5, 5.6**).

**5. Sources to corroborate the impact** (indicative maximum of 10 references)

The following sources of corroboration can be made available at request.


**5.1.** letter from [text removed for publication], Sport Research Director,

**5.2.** letter from [text removed for publication], R&D Manager-Thermal Comfort

***5.3.*** letter from British Cycling, Lead Physiologist *(includes picture of Sir Chris Hoy using the technology at the London Olympics)*

**5.4.** letter from ThermoAnalytics Inc, USA, principal scientist.

**5.5.** Bain, AR., Deren, T.M. and Jay, O., *Describing individual variation in local sweating during exercise in a temperate environment*, European Journal of Applied Physiology 111.8 (2011): 1599-1607, DOI: 7/s00421-010-1788-9

**5.6.** Deren, TM., Coris, E.E, Bain, A.R, Walz, S.M. and Jay, O., *Sweating is greater in NCAA football linemen independently of heat production*, Medicine and Science in Sports and Exercise 44.2 (2012): 244-252, DOI: 10.1249/MSS.0b013e31822cb4e2


**Media Coverage**

Olympic Cycling hot pants:


**5.7.** http://www.youtube.com/watch?v=l7DPB0LQr5c&feature=youtu.be

**5.8.** http://www.runnersworld.com/running-apparel/electric-warm-up-pants

**5.9.** feature article "Pendleton's hot pants helped her win gold" in 'cycling weekly' august 9, 2012, page 34-35 (available from Loughborough University) describing the research in relation to the Olympic performance.

**5.10.** http://www.pocket-lint.com/news/46696/adidas-battery-powered-adipower-hotpants-for-team-gb-olympic-london-2012-track-cyclists