**Thermal Comfort of Winter Cycling Footwear**

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**Background**: Too cold environmental conditions represent the most common reason for commuters not to go to work by bike (Sears et al., 2012). Moreover, the results of the same survey identified wind speed as a factor to significantly diminish the odds of bicycle commuting. Sears et al. (2012) conclude, that the likelihood of bicycle commuting rises 3% with every 1°F increase in morning temperature and decreases by 5% with 1.6kmh$^{-1}$ increase in wind speed. Morning precipitation is another major reason for not to go by bike.

Footwear plays a key role for the overall thermal comfort in cold environment. Cold feet represent a symptom of general cold discomfort (Kuklane, 2013). If the insulation properties of the clothing system are inadequate and athletes feel cold, they will often perceive it in the feet. Kuklane (2013) attributes this to the skin temperature of the feet being normally the lowest because of vasoconstriction. Otherwise, if the feet are insufficiently protected against cold, the perception of cold discomfort will be dominating despite of proper clothing on the rest of the body (Kuklane, 2013).

Considering these thermo-physiological aspects and special requirements during cycling in a cold and partly wet environment, winter cycling footwear has to offer – besides sufficient insulation and a waterproof shaft – also windproof upper material and water impermeable sole construction around the cleat region to protect against splash water.

**Purpose**: The overall goal of the research project was to improve an existing winter cycling shoe towards optimised thermal comfort – also considering the influence of headwind on skin foot temperature. In a first step a computational fluid dynamic analysis (CFD) should be performed to detect the influence of headwind on defined foot regions at three different pedal/foot positions. These findings should be implemented in the further development of the new shoe model. In a second step the newly developed winter cycling shoe should be evaluated within a subject study by means of thermal imaging and subjective perception.

**Methods**: The avatar used in the CFD was generated with MakeHuman™ and imported with standard rig in Blender™ for posing on a bike. The anthropometrics of the avatar were derived from Australian track cyclists (MC Lean and Parker 1989). CFD analyses were done at AirShaper™ using a steady-state RANS (Reynols Averaged Navier Stokes) method with k-omega SST turbulence model. The boundary conditions used are: wind speed: 5.5 ms$^{-1}$; air temperature: 15°C, air density: 1.225 kgm$^{3}$; atmospheric pressure: 101300 Pa. The focus of this study was on the lower leg. The three analysed pedal/foot positions (Fig. 2) were derived from Broker (2003). To focus computational power on this area, the model was cut off just below the knee, a moving ground was applied to avoid artificial flow effects. The qualitative evaluation of the simulation was focused on the general flow patterns (3D trajectories of "air particles") and the pressure and velocity profiles around the foot. 3D wake patterns (iso-surfaces for a total pressure equal to zero) were also considered. No thermal or humidity effects were considered, and local surface pressure and surface streamlines were used as the prime indicator for possible air penetration through the upper material.

Four male bike commuters (∅37±10 years; 176±0,1 cm; 76±11kg; 45±21km weekly "aggregated commuting distance") participated on the subject study. They performed a load profile of 30 min. cycling on a Tacx cycling trainer at a moderate intensity level of 120W with 5 min. rest prior and 5 min. rest after the cycling part. The subjects were tested in a climate chamber at 0±1°C and ~90% relative humidity. Two floor fans were positioned in front of the cyclist generating an airflow aimed at the lower legs of the cyclist. The air velocity around the feet region was 9kmh$^{-1}$. To measure the surface temperature on the skin and the shoe an infrared camera (FLIR E85) was used. The barefoot IR images (dorsal view only) were taken just before and after the cycling activity at room temperature (20±1°C;

~50% rH). Shoe IR pictures were taken in 5 standardized foot positions (dorsal, medial, lateral, posterior, plantar) every 5 minutes during the cycling activity in the climate chamber as well as prior and after the test in the preparation room (at room temperature). Each subject had to cycle in all four shoe conditions (Fig. 3). The difference between the new vs. old Vaude – model is shown in Fig. 4. Subjective feedback focusing foot temperature and moisture (scaling according to DIN 7730) was collected every 5 minutes during the cycling activity as well as prior and after rest.

**Results**: The CFD results display that the pedal/foot position has a substantial influence on surface pressure (Fig. 1 & 2). Especially the "heel-up"-position is strongly affected by headwind. The most important effect in that position is high surface pressure around the dorsum of the foot. Independent of the pedal/foot position the toe area especially the anterior margin of the toes and the space between the toes show a high surface pressure and subsequently a higher risk for (cold) air penetration. Moreover, a high surface pressure can be observed around the anterior aspect of the ankle joint complex (AJC). Therefore, these three locations (toe area, dorsum and anterior aspect of AJC) should offer best insulation, wind- and waterproofed characteristics.

Because of methodological aspects the quantitative assessment of surface temperature immediately prior and after the cycling activity in the preparation room was evaluated. The values displayed in Fig. 5 refer to the temperature loss (difference) between pre and post measurements without shoes. The values represent the average surface skin temperature of the dorsal region of the foot which was defined by a rectangle with always the same size and location. The new Vaude shoe indicates the lowest temperature loss and hence the best insulation characteristics within the tested footwear conditions. The old Vaude model and the winter bike shoe from Northwave exhibit a substantially higher temperature loss of more than 2°C. The thermal images (Fig. 6) of all 4 tested footwear conditions clearly indicate the toe area as the anatomical location with the lowest skin temperature and thus the most vulnerable region to suffer from cold thermal discomfort. The objective results done by thermal imaging are supported by the athletes' feedback regarding subjective temperature perception (Fig. 7). The new Vaude model is judged as the most comfortable and the old Vaude as well as the Northwave model as the least comfortable in terms of temperature. There are no substantial differences in moisture perception between the different footwear conditions.

**Discussion**: Unfortunately, there is only little research available about thermal comfort of athletic footwear in cold weather conditions. Most of the research refers to running and walking in moderate and warm environmental conditions (Auer et al. 2009, Smith et al., 2013; West et al., 2019). However, studies which investigated the thermal comfort of ski boots emphasise the importance of insulation properties and wind resistance (Fauland et al., 2011, Hofer et al. 2014). In addition, Hofer et al. (2014) and Moncalero (2017) point out the importance of keeping the feet and particularly the toes warm during skiing. This goes hand in hand with the present CFD results and the findings based on thermal imaging. In addition, Defraeye et al. (2011) demonstrated based on CFD analysis that headwind affects the convective heat transfer coefficient (CHTC) during cycling. Especially the lower leg and the foot in "heel-up"-position reveal the highest CHTCs.

**Conclusions:** The findings of both CFD analysis and subject study clearly illustrate that the dorsum of the foot and especially the toe region is most susceptible for thermal comfort during cycling in cold weather conditions. In that context appropriate footwear should offer optimal insulation properties and protection against wind and moisture. However, not only the material and the design of the footwear but also the whole foot-sock-footwear system should be considered when optimizing the thermal foot comfort. The material and design interventions applied to the new Vaude shoe clearly confirm the opportunity to improve the thermal comfort, which was not only based on objective data but also on subjective feedback.

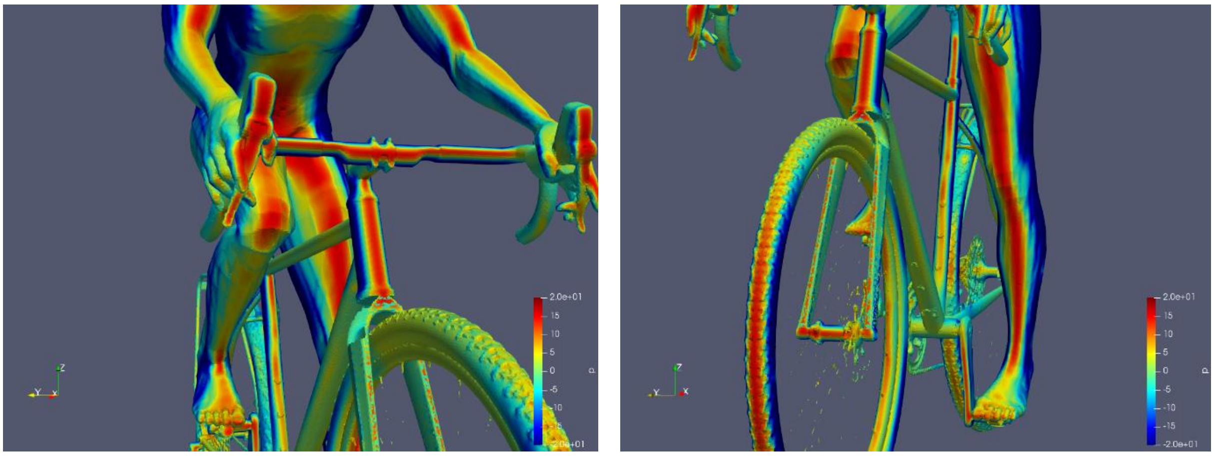

*Figure 1. CFD analysis, images show surface pressure of the left and right lower extremity during cycling*

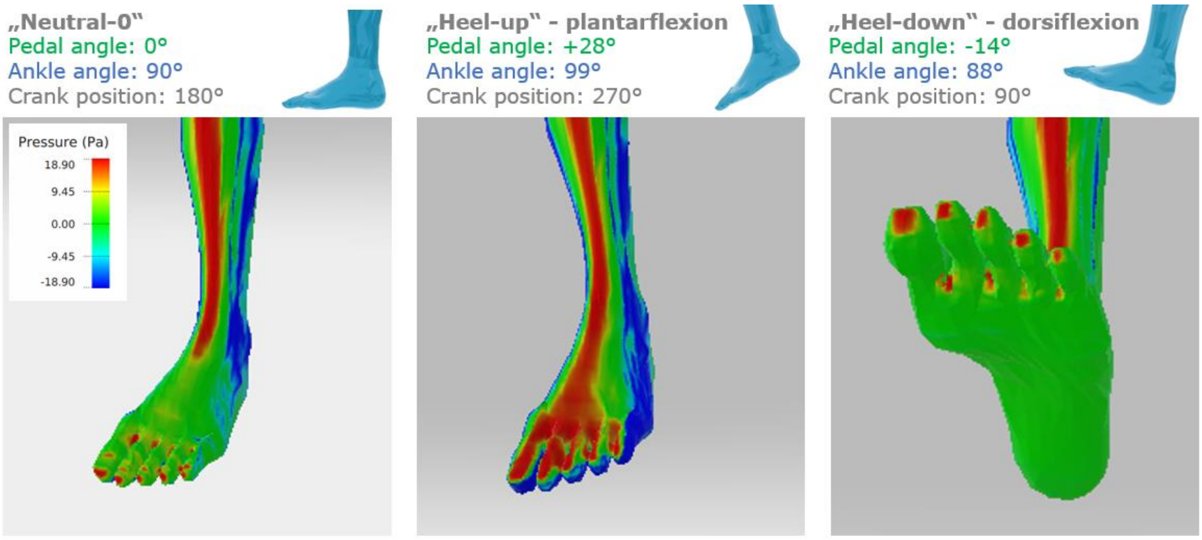


*Figure 2. Surface pressure depending on pedal (orientation) angle; red colour indicates high surface pressure especially around the toe and the dorsum region of the foot*

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|---|---|---|---|
| Vaude- Old Minaki Mid CPX) | Vaude – New Minaki Mid II STX | Shimano MW7 | NorthWave Raptor GTX |

*Figure 3. Footwear conditions for thermography*


*Figure 4. Differences in footwear between the new vs. old Vaude Minakt*

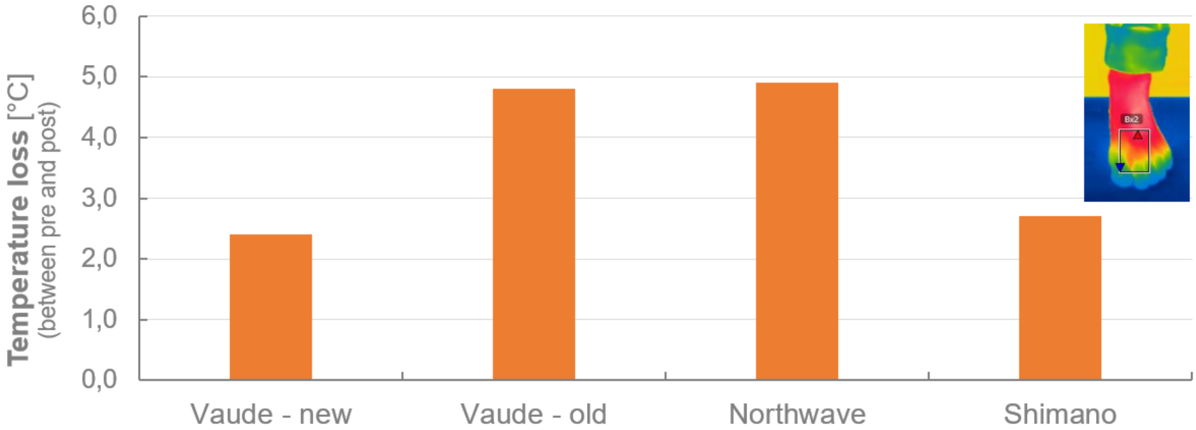
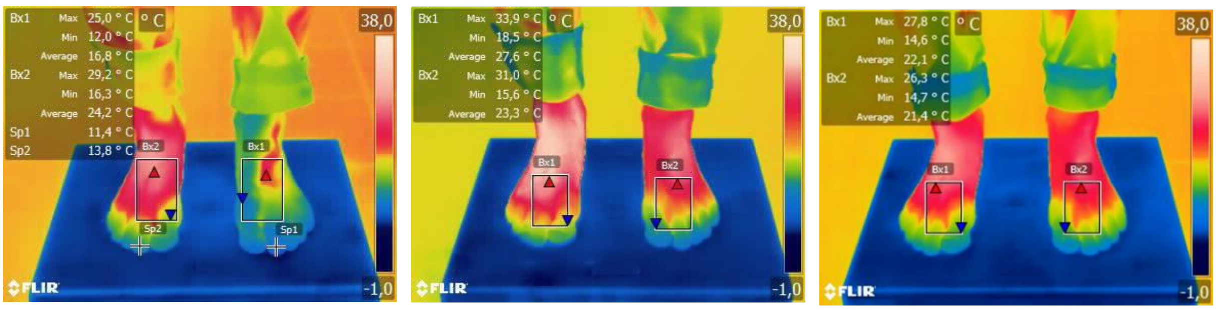



*Figure 5. Temperature loss (difference) between pre and post measurements without shoes; Measurement area: dorsal region of the foot as shown in the thermal image (rectangle)*



Right foot: Vaude
Left foot: barefoot during cycling

Right foot: Vaude – new
Left foot: Vaude - old

Right foot: Shimano
Left foot: NorthWave

*Figure 6. Thermal images of skin surface temperature (dorsal view; same subject); red colour illustrates warmer temperature, blue colder surface temperature*

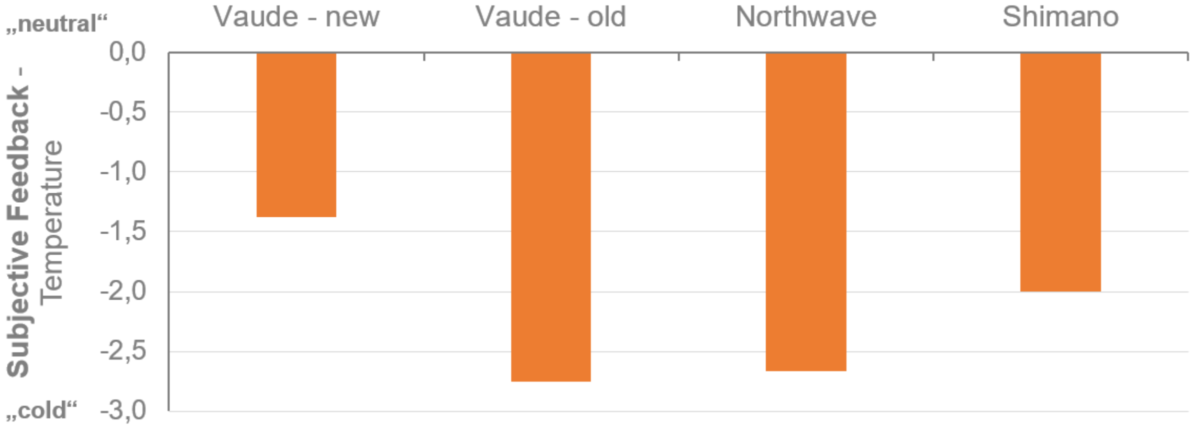



*Figure 7. Subjective feedback of perceived temperature after 30 min of cycling; scaling according to DIN 7730 (+3: hot - -3: cold)*

## References

Auer M, Michel F, Harnisch M., Leimer R (2009) Schuhlima in Sportschuhen. Orthopädieschuhtechnik 9, 18-23.

Broker JP (2003) Cycling biomechanics: Road and mountain. In ER Burke (Ed.), High-Tech cycling (pp. 119-145): Human Kinetics.

Defraeye T, Blocken B, Koninckx E, Hespel P, Carmeliet (2011) J. Computational fluid dynamics analysis of drag and convective heat transfer of individual body segments for different cyclist positions. J Biomech 44(9):1695-701.

Fauland G, Hofer P, Nachbauer W, Bechtold T (2012) Moisture management properties of ski-boot liner materials. Textile Research Journal 82(2): 99-107.

Hofer P, Hasler M, Fauland G, Bechtold T, Nachbauer W (2014) Microclimate in ski boots – Temperature, relative humidity, and water absorption. Applied Ergonomics 45(3): 515-520.

Kuklane K (2013) Footwear for cold weather conditions. In A. Luximon (Ed.), Handbook of Footwear Design and Manufacture (pp. 283-317): Woodhead Publishing.

McLean BD, Parker AW (1989) An anthropometric analysis of elite Australian track cyclists. Journal of Sports Sciences 7(3):247-55.

Moncalero M (2017) High Performance Polymeric Materials for Sport Equipment, Functional Clothing and Footwear: Interactions of Materials, Human Body and Environment in terms of Mechanical, Thermal and Ergonomic Properties. University of Bologna, Italy.

Sears J, Flynn BS, Aultman-Hall L, Dana GS (2012). To bike or not to bike: Seasonal factors for bicycle commuting. Transportation Research Record 2314(1): 105-111.

Smith C, Machado-Moreira C, Plant G, Hooder S, Havenith G, Taylor N. (2013). Design data for footwear: sweating distribution on the human foot. International Journal of Clothing Science and Technology 25(1): 43-58.

West A M, Schönfisch D, Picard A, Tarrier J, Hodder S, Havenith G (2019). Shoe microclimate: An objective characterisation and subjective evaluation. Applied Ergonomics: *78*, 1-12.

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