High-altitude footwear can be more appropriately classified as Personal Protective Equipment (PPE) rather than simply sports equipment. However, there are currently no strict or reliable standards available to accurately assess the thermal performance of cold-protective footwear, apart from the general guidelines defined in ISO 20344:2021. Another possible method for determining footwear insulation is the thermal manikin test (ISO 15831:2004). Although this procedure provides precise and reproducible results, it is expensive and not easily applicable in industrial contexts. Moreover, both of these tests rely on the physical production of the samples that should be tested.

This thesis aims to develop an improved methodology for assessing the thermal performance of cold-protective footwear. To achieve this, three complementary approaches were adopted: experimental, physics-based, and data-driven.

In the experimental approach, the study followed the five-level testing framework, focusing on the first three levels (namely, laboratory testing). This includes apparative tests and in-vivo experiments.

The apparative phase involved characterising the thermal and physical properties of the materials and garments according to ISO 9920:2007 (thermal resistance, R_{cT}), ISO 5084:1997 (thickness), and ISO 15831:2004 (thermal insulation of clothing ensembles). The in-vivo tests, conducted in controlled cold environments, focused on understanding human thermophysiological responses. A key finding was the confirmation of big toe temperature as a reliable indicator of foot thermal comfort, consistent with previous literature, and the identification of a critical safety threshold of 15 °C to prevent frostbite risk. Moreover, a strong zero-lag correlation was observed between mean skin temperature and big toe temperature, enabling the latter to be predicted from the former. These results also contributed to the creation of a comprehensive dataset of body temperature time series under varying ambient, activity, and insulation conditions, an essential foundation for subsequent modelling efforts.

Building on this knowledge, the physics-based approach focused on replicating and validating one of the experimental test protocols through a realistic digital twin of a boot provided by the industrial partner. The model was divided into distinct regions reproducing the actual materials and thicknesses, and was validated against experimental R_{cT} data from the manikin tests. A user-defined material database was developed to ensure accurate input parameters. This approach enabled the virtual estimation of a prototype's R_{cT} value prior to physical production, thus providing the company with a valuable tool to assess footwear thermal performance based on material composition and design.

Finally, the data-driven approach used the dataset obtained from the human tests to develop predictive models of peripheral temperature dynamics. Two different algorithms were compared: a statistical autoregressive model (SARIMAX) and a neural network architecture employing Long Short-Term Memory (LSTM) layers. Both were trained using categorical inputs such as ambient temperature, activity level, and footwear insulation (derived from Computational Fluid Dynamics results or from the physical thermal manikin tests R_{cT} estimation or from the physical thermal manikin tests). The models aimed to predict big toe temperature, used as an indicator of foot thermal comfort, over time. Specifically, the time in minutes taken by the big toe temperature curve to reach 15 °C was defined as the Duration of Safe Exposure, forming the second evaluation parameter for footwear thermal properties. The LSTM-based model demonstrated higher accuracy and generalisation capability, highlighting the potential of integrating experimental, computational, and data-driven methods into a unified framework for footwear thermal performance assessment.