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A 3D Printed Thermal Manikin Head for Evaluating Helmets for Convective and Radiative Heat Loss

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Abstract. Thermal performance of three bicycle helmets for radiative and convective heat loss was evaluated through heat loss experiments in a wind tunnel. A 3D printed thermal manikin head of a 50th percentile western male population was developed. Thermal performance of a helmet was quantified by comparing the manikin head heat losses with and without helmet. Experiments were performed for two air velocities: 1.6 m/s and 6 m/s. An infrared heat lamp positioned above the manikin simulated the effect of solar load. The results from the experiments showed a convective cooling efficiency between 89% and 96% for open helmets and between 78% and 83% for closed helmets. The radiative heat gain ranged from 3.5 W to 4.5 W for open helmets and 5 W to 8 W for closed helmets.

Keywords: Heat transfer · Convective heat loss · Radiative heat gain
Thermal manikin head · Wind tunnel · Helmet thermal performance

1 Introduction

Cycling is a popular mode of transport in different parts of the world owing to its environmental friendliness and health merits. However, it is also the third most dangerous form of transport resulting in injury and mortality. Head injury is reported as the direct cause of death in about 69% of the cycling fatalities [1, 2]. Therefore, protective headgear, i.e. helmets, play an important role in user safety. The usefulness of bicycle helmets in reducing risks of head injury has been shown [3–5]. This has resulted in numerous research studies on improving helmet safety leading to changes in helmet

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design. [6–8]. Despite the advantages of protective headgear, helmet usage varies substantially among users. Further research into this topic indicated that physical and thermal discomfort may play a role in the users' decision against wearing helmets [34]. Though helmets can provide thermal benefits in cold conditions [12] helmets may receive an adverse reaction from users in warm conditions. For example, motorcycle helmet usage rates in Italy are reported to be 93% and 60% for Northern and Southern Italy, respectively. A difference that can at least be partially explained through headgear induced thermal discomfort in warm environments [9–11]. Therefore, an in-depth study on thermal discomfort and its influence on user may allow designing helmets with increased user acceptance. Studies used in testing user comfort, mass and heat transfer during helmet usage fall into two categories: subject studies and object studies.

Subject studies or user trials allow gaining insight into the global or local heat loss of test persons. These studies are done to understand a multitude of parameters that influence thermal sensation while using products that come in contact with the user. Thermoregulation between the user and the environment in colder and warmer environments were studied using subject studies. Several subject studies have monitored the effects of sweat on heat transfer and in turn on thermal comfort. Quantification of sweat rates using ventilated capsules [13, 14] and methodologies using absorbent pads [15] have helped in understanding the evaporation mechanism and the existence of a correlation between local and global sweat rate [13, 15]. Taylor and Machado-Moreira [14] developed predictive equations for sweat rate in head at rest or exercising using results from user trials. Results of user trails are unfortunately not always easy to use for generalization towards helmet improvement due to high individual differences between test subjects. Hence, object studies or bio-physical methods have gained importance. Biophysical methods have focused on thermal manikin head studies. These methods use thermal manikins developed to resemble anatomically correct headforms that mimic the behavior of the human head in terms of heat and mass transfer with the surrounding environment. Several headforms have been developed for the testing of head gear [16–20]. Some of these commercially available thermal manikin headforms were used in testing of industrial helmets [16, 19–21] and sports helmets [22–24]. These thermal manikins were developed by researchers for different purposes resulting in differences in number of segments, measurement methodology and data collection. However, the basic principle remains the same. The surface of the thermal manikin is maintained at a fixed temperature (test conditions) using heating elements and embedded temperature sensors and the power required to maintain this surface temperature over a steady-state period is recorded. This power is quantified as the combined heat loss due to convection, conduction and radiation. Several studies were performed using thermal manikins for studying heat transfer with head gear. Effect of solar radiation on the net heat transfer from the head with and without headgear was studied [22, 25]. For example, vent induced heat transfer in motorcycle helmets [26] and analysis of the comfort angle dependence [28] are research studies where thermal manikins were extensively used. Thermal manikin studies have also resulted in improvements in geometry and construction of headforms. Evaporative heat loss was simulated to a limited extent [24] using moisture releasing ducts on the manikin surface. In addition, manikins have also been used to test the influence of hair [24]. The next step in the development of thermal manikins is to couple these thermal manikins with numerical models simulating thermal physiological responses [28]. This results in an increase in complexity and accuracy of thermal manikins and also the variety of parameters that can be measured using headforms. For instance, a multi-segmental sweating manikin controlled by a CFD thermoregulatory model was developed [29] to evaluate comfort in vehicle environments. In some cases, CFD implementation is replaced by traditional control models [30, 31]. When coupled with numerical models, the thermal manikin act as a sensor providing feedback to the numerical models.

Overall, thermal manikin headform experiments provide objective data with reduced experimental variations as compared to subjective studies with test persons. Subjective studies may however provide more realistic results. Unfortunately, current thermal manikin heads are not always anthropometrically realistic, resulting in biased results when headgear is evaluated considering disproportionate spaces between head and helmet.

Within this research it is hypothesized that the 3D anthropometric information contributes to the creation of thermal manikin heads that can produce more realistic results. The objective of the study is to evaluate the capacity of a 3D printed anthropometric thermal manikin head for quantifying the thermal performance of headgear in terms of convective and radiation heat transfer.

2 Heat Transfer Between User and Environment

The core temperature of the human body is maintained at approximately 37 °C in moderately cold, neutral and moderately warm environments. The human body has different thermo-physiological mechanism to maintain its homeostasis such as shivering and vasoconstriction in cold, and evaporation and vasodilation in warm environments. During homeostasis, the heat loss through the skin and respiration approximates the internal heat production and heat storage in the human body is close to zero. During heat exposure, the heat storage in the human body increases. Heat storage in the human body can be expressed as:

$$\mathrm{S} = \mathrm{M} - \mathrm{W} - (\mathrm{E}_{\mathrm{res}} + \mathrm{C}_{\mathrm{res}} + \mathrm{E}_{\mathrm{sk}} + \mathrm{C}_{\mathrm{sk}} + \mathrm{K} + \mathrm{R}) \tag{1}$$

where M is the metabolic rate and W is the work rate, quantifying the rate of heat production. Heat loss/gain is the result of the heat transfer by evaporation (E), convection (C), conduction (K) and radiation (R). Evaporation and convection occur through respiration (res) and skin (sk) and S is the heat storage in the human body which is expressed in kJ/h or W. The human head exhibits unique heat transfer properties owing to its lack of vasoconstriction responses. In addition to this, the lack of clothing or insulation that protects other parts of the body results in higher transfer of heat from the head. The environment heat transfer from the head is non-homogenous which may result in different parts of the head exhibiting different heat transfer characteristics. Studies show that the nose exhibits higher rate of cooling and heating than the face and cheeks [33]. Thus, modelling and testing of multiple modes of heat transfer can be a complicated task. For bicycle helmets with a layer of insulating expanded polystyrene, heat loss is predominantly defined by convective heat loss and evaporative heat loss. Convective heat transfer is defined by:

$$\dot{Q}_{cs} = h_c A(T_h - T_a) \tag{2}$$

where,$\dot{Q}_{cs}$ is the convection heat transfer per unit of time, A is the surface area of the object, h_c is the convective heat transfer coefficient, T_h is the temperature of head surface, T_a is the temperature of the air/fluid. The evaporative heat dissipation is given by

$$\dot{Q}_{ls} = h_e A(P_{sk} - P_a) \tag{3}$$

where, $\dot{Q}_{ls}$ is the evaporative heat transfer per unit of time, A is the surface area of the object, h_e is the evaporative heat transfer coefficient, P_{sk} is the vapour pressure of skin, P_a is the vapour pressure of the air/fluid. In addition to heat transfer through convection, there is also radiant heat exchange which can be calculated as:

$$\dot{Q}_r = \varepsilon\sigma\left(T_h^4 - T_c^4\right)A_c$$

where, $\dot{Q}_r$ is the radiant heat gain/loss rate (W), T_h is the temperature of hot body (K), T_c is the temperature of the cold body, A_c is the surface area of the object, ε is the emissivity coefficient of the object, σ is Stefann-Boltzmann constant (5.67×10^{-8} W/m^{2}K).

3 Materials and Methods

3.1 Ermal Manikin

A Thermal manikin head was developed using shape modelling and 3D printing. The external shape of the thermal manikin was generated using parametric shape modelling. 100 MRI scans of adult western population in the age group of 20-30 years were used as input (from ICBM database) for shape modelling process. From the scans, using segmentation, parametrization and sampling, a preliminary model was obtained [32]. This was followed by subjecting the preliminary model through principal component analysis. The principal components of the analyzed model were then mapped with anthropometric measurements (Fig. 1.) resulting in a 3D anthropometric shape model.

The head shape model represents the biophydelic head-shape of a 50th percentile western head. This head shape was classified into eight measurement regions. These measurement regions were defined according to test requirements and named as follows: facial, ocular, frontal, parietal, superior occipital, inferior occipital, left and right temporal and neck. The thermal manikin head has two layers as shown in Fig. 2, an inner layer of thickness 2 mm that was lined with heating elements connected to a power source to maintain a desired temperature on the surface. In addition to the heating elements, temperature measurement sensors were installed in each measurement zone as shown in Fig. 2

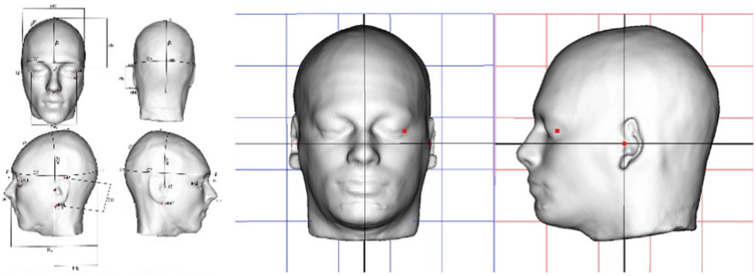

Fig. 1. Annotation points and coordinate system used in the anthropometric measurements (Image source: Lacko et al. 2015)

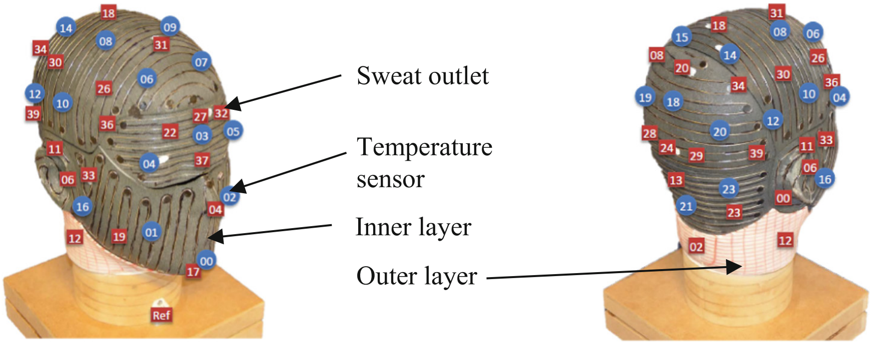

Fig. 2. Thermal manikin layers with temperature sensors and sweat openings

The sensors provided zonal temperature feedback and assist in maintaining constant zone temperature by controlling the power input. The outer layer (thickness: 2.5 mm) of the thermal manikin head was provided with openings on the surface to simulate sweat which plays an important role in the evaporative heat loss (latent heat loss). These openings to simulate sweat are connected to a pumping mechanism that pumps sweat/fluid to simulate sweating at a defined sweat rate. The surface heat loss of individual zones is controlled through zonal temperature data. Zonal heat loss and temperature is monitored at 1 Hz. The thermal manikin is mounted on a platform that allows adjusting its angle compared to the vertical direction.

3.2 Wind Tunnel

A quasi laminar flow is induced through the exhaust of an open-loop wind tunnel. The thermal manikin head is placed 50 cm in front of this wind tunnel exhaust, as shown in Fig. 3(i). Then, a climate chamber encloses the wind tunnel such that temperature and relative humidity can be controlled at ±1 °C and ±5%, respectively with the use of 2 temperature sensors (Vernier temperature probe and DHT22 temperature and humidity sensor) and the chamber temperature is maintained with the help of HVAC system equipped with two 3 kW heaters and 12 kBTU cooling system controlled using inbuilt

Fig. 3. (i) Thermal manikin positioned at the outlet of the wind tunnel (ii) radiative heat transfer setup with heat lamps

thermostats. A radial fan driven by a 7.5 kW synchronous motor regulated using a frequency regulator allows creating an operational air velocity between 0.1 and 15.0 m/s.

3.3 Radiative Heat Transfer Setup

The radiative heat transfer setup was based upon the research of Paul Brühwiler [25]. To simulate an external heat source, a 150 W infrared heat bulb was used. The heat source is fixed such that it makes an angle of 60° with the manikin base (Fig. 3(ii)). Two heat lamps were used as required and the output of the heat lamps can be controlled using a power regulator resulting in 3 different power output settings – low, medium and high. The manikin was placed vertical and was exposed to the heat lamp from the front. This heat exposure is chosen to simulate an intermediate radiation situation with the scalp and the face regions achieving comparable exposure. Convective heat transfer tests as describes in Sect. 3.4 were carried out but with an additional heat source (IR lamps). The difference between the heat transfer values with and without external heat source is defined as the radiative heat gain.

3.4 Test Conditions

Steady state heat transfer experiments were conducted for a duration of 60 min. Test duration was set to 60 min since the experiments required 20 min to reach stable results. Two different air velocities (1.6 m/s and 6 m/s) were used to simulate low and high cycling speeds. The thermal manikin is placed in a vertical position (i.e. with an angle of inclination of 0°). The surface temperature of the manikin head was set to 30 °C and the temperature of chamber was maintained at 20 °C. The goal was to maintain a 10-degree temperature difference (ΔT) between the manikin and the environment. Convective heat loss experiments were done for three commercial helmets (Fig. 4.) that are characterized as: Open helmet with internal channel (OHIC), open helmet without internal channel (OHWIC) and closed helmet (CH).

Fig. 4. (i) Thermal manikin or nude headform (ii) open helmet with internal channel (OHIC) (iii) open helmet without internal channels (OHWIC) (iv) closed helmet (CH)

4 Results and Discussion

4.1 Convective Heat Loss

The convective heat transfer values for a nude manikin head and three manikin heads with helmets are shown below in Fig. 5. Convective heat loss at 6 m/s is in the range of 28.5–34.5 W whereas at 1.6 m/s is in the range of 15.6–20.5. Convective heat loss of the thermal manikin head with helmets is lower than for the nude manikin head. The tested helmets reduce the convective loss than the thermal head by providing same shielding against the imposed convective currents (wind).

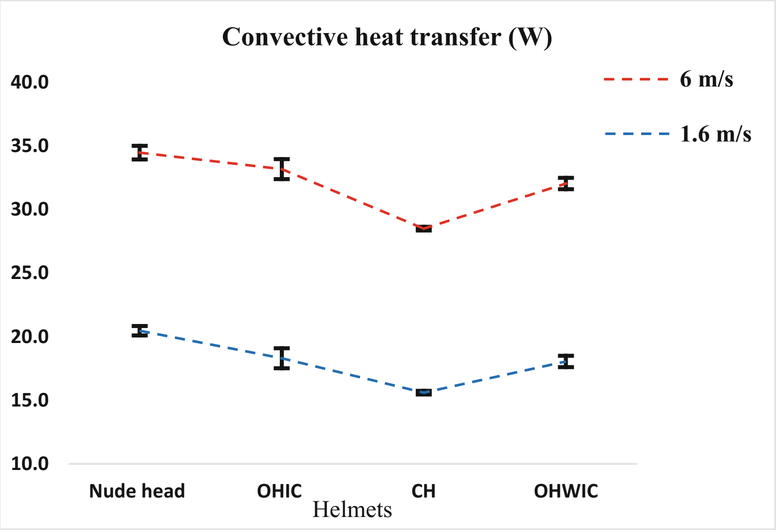

Fig. 5. Convective heat loss from thermal manikin at 6 m/s and 1.6 m/s (95% CI)

Helmet design does affect the rate of heat transfer to the environment. For example, convective heat transfer from the open helmet with internal channels (OHIC) is almost similar to that of the nude head (Table 1) reaching 96% and 92% of the nude head losses for high (6 m/s) and low (1.6 m/s) speeds respectively. For an open helmet without internal channels (OHWIC), the convective heat transfer efficiency compared to nude head is 93% and 90% for high (6 m/s) and low (1.6 m/s) speeds respectively. For the closed helmet (CH), convective efficiency is limited to 83% and 78% for high (6 m/s) and low (1.6 m/s) speeds respectively. These results clearly indicate that open helmets with internal channels are more efficient in dissipating the heat generated between the head and the helmet at moderate cycling speeds, as compared to closed helmets.

Table 1. Efficiency of tested helmets $\left(\frac{\dot{Q}_{helm}}{\dot{Q}_{nude}} x100\right)$

S.No	Helmet	Efficiency (%)	
		6 m/s	1,6 m/s
1	OHIC	96,2	91,6
2	OHWIC	92,9	90,3
3	CH	82,7	78,0

4.2 Radiative Heat Gain

Results from the radiative heat gain experiments are plotted in Fig. 6.

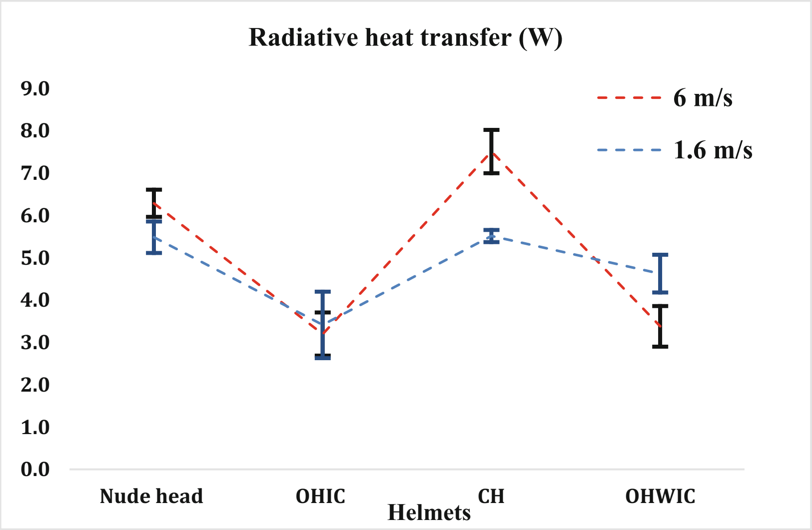

Fig. 6. Radiative heat gain at 6 m/s and 1.6 m/s (95% CI)

The nude thermal manikin has radiative heat gain of 6.3 ± 0.7 W at 6 m/s and 5.5 ± 0.3 W at 1.6 m/s. In relative terms, radiative heat gain has such a large effect on the overall heat loss of the manikin head as compared to a change in air velocity. Moreover, the results show a higher heat gain for the nude thermal manikin and a closed helmet structure than the evaluated open helmets. For instance, the radiative heat gain for the open helmets was 4 ± 0.5 W and 3.5 ± 0.8 W for 6 m/s and 1.6 m/s respectively, whereas for the closed helmets 7.5 ± 0.5 W and 5.5 ± 0.5 W were obtained. Although vents expose same regions of the head directly to the external radiant source, the associated higher convection between the helmet and the head prevents the temperature of helmet internal surface from increasing so much as far the closed helmet. In turn, this implies lower radiant exchange with the helmet inner surface, for the case of the open helmets. In other words, the closed helmet may trap the heat from the radiative heat source resulting in higher heat gain values.

5 Conclusion

This study shows that the 3D printed thermal manikin head representing a biophydelic head-shape of a 50th percentile western head can be used to test convective and radiative heat exchanges with and without helmet. These results can be considered to be more accurate than the test results from standard headforms since the manikin head-shape was derived from anthropometric-based shape modelling. The results also show that open helmets perform better in different air velocities for both convection and radiation experiments. Closed helmets may serve as a direct shield from incoming heat source but heat entrapment occurring between head and helmet as a result of this design may counter the shield effect entirely. Among open helmets, helmets with internal channels removed heat more efficiently than helmets without channels. Hence this research suggests that the presence of channels in a closed helmet design may improve the helmet heat transfer.

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