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A review on ergonomics of headgear: Thermal effects

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ABSTRACT

The thermal effects related to wearing headgear are complex and different studies have investigated single parts of this topic. This review aims at summarizing the different findings to give a complete overview on this topic as well as to suggest new perspectives. Headgear increases head insulation and therefore is mainly problematic under warm conditions, which is the focus of this review. Helmets do not affect physiological parameters other than the local skin temperature and sweat rate. However, the head is among the most sensitive body parts related to thermal comfort, thereby directly affecting the willingness to wear headgear. Several methods have been used to study thermal aspects of headgear, which could be categorized as (i) numerical, (ii) biophysical, (iii) combined numerical and biophysical, and (iv) user trials. The application of these methods established that heat transfer mainly takes place through radiation and convection. Headgear parameters relevant to these heat transfer pathways, are reviewed and suggestions are provided for improving existing headgear concepts and developing new concepts, ultimately leading to more accepted headgear.

Relevance to industry: This review provides a sound basis for improving existing headgear concepts. Firstly, a concise overview of headgear research related to thermal effects is given, leading to empirically based improvement suggestions and identification of research fields with a high potential. Finally, relevant research methods are described facilitating evaluation in R&D processes.

1. Introduction

Headgear is widely used in both occupation and leisure; it is used as a fashionable accessory or as an optional/mandatory means of protection. Substantial research attention went to optimizing its protective abilities (Aare et al., 2004; Cui et al., 2009; Deck and Willinger, 2006; Mills and Gilchrist, 2008). However, there is evidence that thermal comfort of headgear is suboptimal in neutral and warm environments. In fact, thermal discomfort is considered as a reason not to wear protective headgear (Li et al., 2008; Patel and Mohan, 1993; Skalkidou et al., 1999). For instance, Servadei et al. (2003) reported motorcycle helmet usage rates in the Northern and Southern Italy of 93% and 60%, respectively. This could at least partly be due to higher levels of warmth perception and/or thermal discomfort in warmer climates (Orsi et al., 2012; Papadakaki et al., 2013). Improving thermal comfort of headgear is likely to improve the willingness to wear (protective) headgear, and motivated an increasing number of studies, of which most were published in the last decade (Fig. 1). The available body of literature allows for a valuable first review of this literature. The recent rise of these publications indicates the need for a review for an increasing number of scientists active in this field. Moreover,

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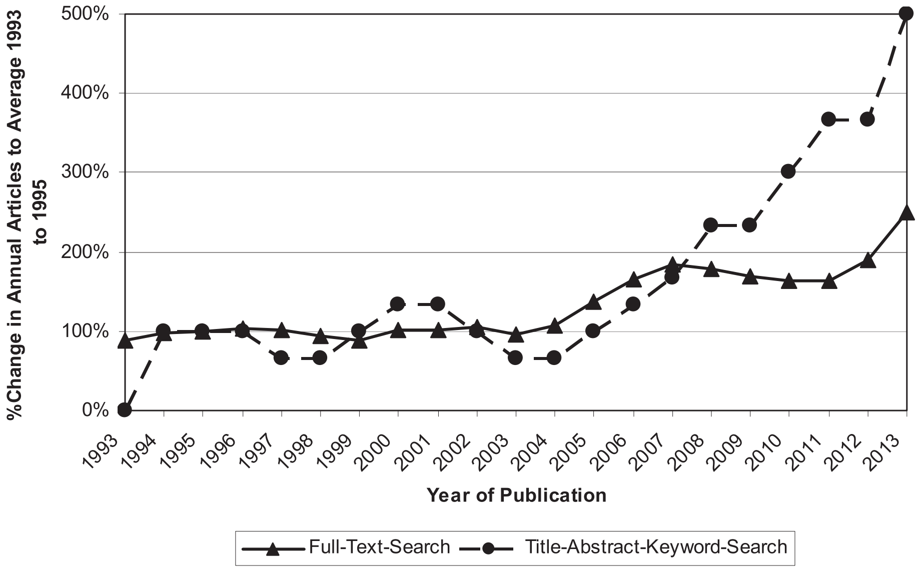

Fig. 1. Percentage change in annual publications concerned with headgear thermal ergonomics during the past two decades compared to the values averaged over 1993–1995. Article searches were performed in SciVerse and ScienceDirect® on 15.05.2013 for: pub-date > 1992 AND (headgear OR helmet) AND (ergonomics OR thermal OR physiology OR "mass transfer" OR "heat transfer") to occur in the full text or in the title-abstract-keywords, respectively. Series were smoothed by 3-years backward moving averages.

warm environments are of special interest for comfort impairment, given that headgear increases the thermal insulation and will thus provide a benefit in cold environments.

The aim of this manuscript is to provide an overview and synthesizes of the available evidence pertaining to the thermal aspects of headgear and to suggest improvements for existing and novel headgear concepts. Publications are reviewed extends beyond headgear used in an industrial setting it rather reviews relevant literature from all types of headgear, distilling patterns applicable to all types of headgear, including those used in the industry. While headgear generally refers to everything one can wear on the head, most studies focused on headgear designed to have specific impact protective properties. Such headgear is often referred to as helmet, a definition we also used in this review. First, the known effects of wearing headgear on humans are described in detail, with focus on thermal physiology and cognition (Section 2). Then, the biophysical heat and mass transfer of a headgear-head system is presented (Section 3). Section 4 reviews relevant methods utilized in studies of headgear properties related to heat and mass transfer including manikins and thermal physiological user trials. The last section (6) gives selected empirical data on results that could lead to improvement of the current headgear design.

2. User and the environment

This section introduces the basics of the human interaction with the thermal environment, which is determined by the environmental physical characteristics (i.e., air and radiant temperatures, humidity and wind) and by the individual factors (e.g., activity level and clothing worn). First the heat balance is explained, followed by the consideration of the local heat balance and related physiological responses at the head. Finally, user-related thermal effects of headgear on comfort, performance and health are discussed.

2.1. Body heat balance

The maintenance of a core body temperature at around 37 °C dictates the existence of a heat balance between the body and its environment. This heat balance represents a dynamic relationship between the heat generation within the body and the heat transfer between the body and the environment. The basic heat balance equation is (Blatteis et al., 2001):

$$S = M - W - (E_{\mathrm{res}} + C_{\mathrm{res}} + E_{\mathrm{sk}} + C_{\mathrm{sk}} + K + R) \quad (1)$$

where M is the metabolic rate and W work rate. In most cases $M - W$ results in the rate of heat production. E, C, K, and R are heat transfer through evaporation, convection, conduction, and radiation. E and C occur through respiration (res) as well as at the skin (sk). The quantity of these heat transfer pathways depend on the environmental conditions and on thermal properties of materials covering the body (e.g., clothing and headgear) as well as hair on the head which provide substantial thermal insulation (Section 3.3). The sum of all these quantities provides the rate of heat storage (S). The units of these parameters are typically given as $\mathrm{kJ\ h^{-1}}$, W, or expressed in relation to unit body surface area as $\mathrm{W\ m^{-2}}$. A positive S leads to an increase in body temperature.

When exercising in the heat under circumstances of forced convection, heat loss from the head was estimated at 200–250 W (Rasch et al., 1991). Given a gross efficiency of cycling of the order of 20% (Ettema and Loras, 2009; Hettinga et al., 2007), which is lower than Rasch et al. (1991) used in their manuscript, this results in heat loss from the head of one-quarter to one-third of the total metabolic body heat. This is substantially higher than the head's proportion (7–10%) of the total body surface area. Another study (Nunneley et al., 1971) reported that cooling the head by a cap with water perfused tubes could remove 30% of metabolic heat produced at rest and 19% when exercising at 50% of maximal oxygen uptake, indicating the importance of the head as a heat sink. Thus, the head has a considerable heat loss capacity, which will be described in more detail in the sections below.

2.2. Heat transfer at the head

2.2.1. Cooling

Unique to the head is the lack of vasoconstriction responses in the skin of the head (Cheung, 2007; Froese and Burton, 1957). Since the head is often not fully covered with clothing or headgear, it