International Journal of Industrial Ergonomics 66 (2018) 169–176

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

A comparative study on the mechanical performance of the protective headgear materials to minimize the injury to the boxers' head

Reza Razaghi[a], Hasan Biglari[a], Alireza Karimi[b,*]

[a] Mechanical Engineering Department, University of Tabriz, Tabriz, Iran
[b] Department of Mechanical Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

ARTICLE INFO

Keywords:
Boxing
Injury
Headgear
Expanded propylene foam
Expanded polystyrene foam
Polyvinyl alcohol sponge
Finite element

ABSTRACT

This study was aimed at performing a dynamic Finite Element (FE) study to compare the performance of three different materials, i.e., the expanded propylene (EPP), expanded polystyrene foam (EPS), and polyvinyl alcohol sponge (PVA), in reducing the amount of injury as a result of a right hook to the face. To do that, a well-verified FE model of the skull, headgear, and punch was employed to simulate the hook in the zygomatic bone of the skull and the resulted von Mises stress in that under three different energy absorbing headgear materials were calculated. The mechanical properties of the EPP were obtained from the literature, while the mechanical properties of the PVA and EPS were measured by the authors. The mechanical properties of the EPS were measured under six different strain rates, and the mean mechanical values were assigned to the model. The experimental results revealed the values of 0.44 ± 0.084 (MPa), 1.47 ± 0.087 (MPa), 0.98 ± 0.11 for the elastic modulus, stress and strain failures, respectively. The numerical FE results showed the von Mises stress of 11210 MPa as a consequence of hook in the skull. After wearing the headgears, the stresses of 364.40, 640.3, and 79.34 MPa were observed for the EPP, PVA, and EPS, respectively. The results suggest the effectiveness of the EPS compared to two other materials in controlling the amount of injury in the face of the boxers. Finally, a composite structure of these three materials were employed which enabled to lessen the stress in the face to 30.56 MPa.

1. Introduction

Boxing is usually accompanied with severe forms of injuries to the head, such as the concussion as well as vertigo as cerebral injury (Zazryn et al., 2006). The face or scalp has been ranked as the most common locations of the injury within the head among the amateur and professional players (Bianco et al., 2005; Timm et al., 1993). Naturally, such injuries to the head are severe enough to trigger knockout as a consequence of significant punch load (Jordan and Campbell, 1988). The headgear is the most important safety tool of the boxers since it enables to minimize the transferred load to the head and, as a result, increase the safety level of the players during the game. However, the materials employing for the headgears can affect the safety level of the players.

Different types of energy absorbing materials can be used for the headgears, including the foams, rubbers, and sponges. Foam materials owing to their low density (low weight) as well as high energy absorption capacity are the ones which preferred. These foamy structure materials fall into two different groups, i.e., recoverable and unrecoverable. A good example of the recoverable foam is expanded propylene (EPP) which is being used in helmet protectors due to its multiple impact resistance ability (Swarén et al., 2013; Post et al., 2013). The advantage of the EPP materials relates to the structure of their cells as they enable to absorb the impact energy by squeezing the air inside their cells without any damage to the structure of the cells' walls. The structure of the EPP pores is displayed in Fig. 1a. Although EPP can recover its original shape after unloading due to their walls' structure, their proficiency in absorbing the impact energy is not as suitable as unrecoverable foams. EPS is an unrecoverable foam which has a higher energy absorption capacity and lower price in comparison to the EPP foam (Shuaeib et al., 2007). However, it should be noted that EPS constantly deforms during the impact by crushing the walls of the cells and, subsequently, after each impact the capacity of the impact energy absorption decreases (Raps et al., 2015). The structure of the EPS pores is displayed in Fig. 1b. Although the advantages of the EPP weigh up the EPS in terms of recoverability and controlling the amount of injury to the head of the boxers for a longer time (Ayan, 2013), both materials have been used for headgear productions. EPP despite its similarity to the EPS in terms of manufacturing process, has a higher elastic modulus.

---

[*] Corresponding author.
E-mail address: karimi@kyudai.jp (A. Karimi).

https://doi.org/10.1016/j.ergon.2018.03.004
Received 14 August 2017; Received in revised form 9 February 2018; Accepted 19 March 2018
0169-8141/

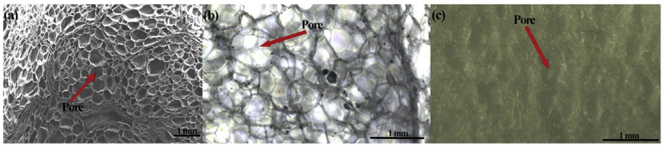

Fig. 1. The **(a)** pore structure of the expanded polypropylene (Hossieny et al., 2013) (Permission/license is granted to use this image), **(b)** expanded polystyrene, and **(c)** polyvinyl alcohol foams. All these three foams are considered as open-cell foams with interconnected pores.

Another foamy open cell material which has been suggested as a suitable energy absorbing material is polyvinyl alcohol sponge (PVA). The microstructure analysis on the PVA revealed that it has an interconnected network of struts or plates, which forms the edges and faces of cells, and provides excellent mechanical properties (Gibson and Ashby, 1997). The structure of the PVA pores is displayed in Fig. 1c. Recent dynamic Finite Element (FE) simulations by the authors well certified the significant ability of the PVA in reducing the amount of injury regardless of the impact angle (Karimi et al., 2014a, 2014b). Furthermore, Karimi et al. (2016a) showed the advantage of the PVA over the EPS as a bicycle helmet under normal impact loading in diminishing the transferred load to the head. Their results showed the von Mises stress induces as a result of using the PVA helmet is two times lower than that of the EPS helmet. Latest studies also well showed the suitable mechanical recoverability of the PVA under a cyclic loading (Karimi et al., 2014c) not only in the axial but also in the transversal directions (Karimi and Navidbakhsh, 2014a). The authors recently also showed that the PVA can be modeled as a visco-hyperelastic material (Karimi et al., 2014d) due to its ability to keep its proper mechanical properties at various loading conditions (Karimi et al., 2014e, 2014f) under different circumstances (Karimi et al., 2014g).

We hypothesized that the energy absorbing protective capacity of the EPP, EPS, and PVA principally is related to their density and thickness. Stereotypically, the thicker the material is, the better the protection, and the denser the material is, the higher damp of the impact energy. As it was pointed out, each of these materials has its own pros and cons. EPP can recover its initial shape after the impact while the EPS despite its suitable energy absorbing capacity does not enable to recover its original shape. PVA not only can recover its structure after the impact but also can retain its mechanical ability under various loading rates and conditions. This study was aimed at investigating the protective ability of headgear made of EPP, EPS, and PVA in controlling the injury to the human face (zygomatic bone) as a consequence of hook via a Three-Dimensional (3D) skull FE model. Considering the advantage and disadvantage of each of the discussed headgear materials, the authors employed a composite structure of these three materials to be able to make benefit from the plus points of each of which in reducing the injury to the boxer's head during the game.

2. Materials and methods

2.1. Experimental measurement

Three headgear materials were planned to be numerically simulated. Since the mechanical properties of the EPP and PVA were obtained from the literature, the mechanical properties of the EPS were aimed to calculate under various loading rates. To do that, the initial dimensions of the EPS samples, including the width × length × height were measured precisely as ~20 × 20 × 15. The EPS samples were then mounted between two flat compressive gripper of the testing machine with 40 mm circular diameter (DBBP-20, Bongshin Company, Seongnam, Korea) equipped with a 50 kgf load cell as presented in Fig. 2. After eight cycles of preloading/preconditioning to dissipate the residual stress of the foams, the tests were started at six different strain rates, including 5, 10, 20, 30, 40, and 50 mm/min by the action of a servo motor (Karimi et al., 2013, 2014h). For each strain rate, 5 EPS samples have been tested. The uniaxial compressive test was performed at the temperature and humidity of 25 °C and 40% (AcuRite, California, United States), respectively, until the failure of the foams. The deformation of the samples was also measured thru three Charged Coupled Device (CCD) high speed video camera (Sony Corporation, Tokyo, Japan). The video cameras enabled to capture 280 frame/second with the resolution of 2048 × 1088 pixels which provides very accurate data for further processing. The basic principle for the processing work is provided by the motion analysis software, namely Simi Motion® 2D/3D (Simi Reality Motion Systems GmbH, Max-Planck-Straße, Unterschleiβheim, Germany). This is the simplest type of test and forms the basis for the definition of both σ_f (failure stress) and E (elastic modulus). The stress within a material, σ, is defined as the compressing force being exerted on a material in both directions, F, divided by the initial cross-sectional area of the object normal to the forces, A:

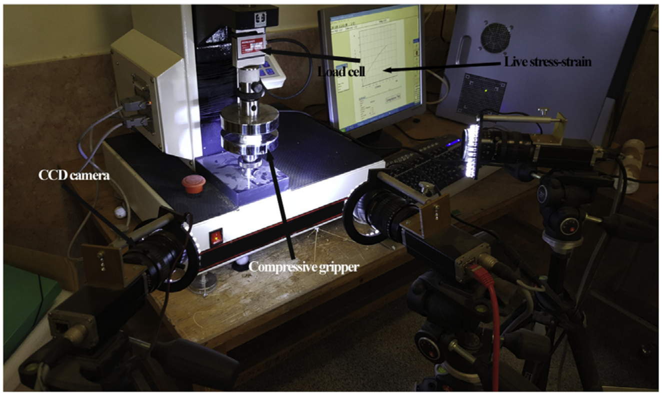

Fig. 2. The mechanical properties of the expanded polystyrene foam were measured through the compressive test. The samples were compressed by the compressive grippers of the machine and the force and displacement were measured thru the load cell and digital image correlation technique. The dimensions of the samples were measured by a digital caliper.

$$\sigma= \frac{F}{A} = \frac{F}{w\times t_0} \tag{1}$$

where w and t_0 are the width and initial thickness of the specimen, respectively. At any point during a uniaxial compression test, the material's stress is determined by how much force the material is being exerted compared to the original cross-sectional area. The failure stress is then the maximum force that objects can tolerate per unit cross-sectional area, which corresponds to its compressive strength. If we take the change in length, called the extension, Δl, and divide this by the original length, l_0, we obtain a quantity called the strain, ε, which is often expressed as the percentage change in length.

$$\varepsilon= \frac{l-l_0}{l_0} = \frac{\Delta l}{l_0}, \quad \text{or} \quad \varepsilon= \frac{\Delta l}{l_0}100\% \tag{2}$$

At any given σ, an object will extend by some amount and so will have a particular ε. The Young's modulus, E, can then be defined as:

$$E= \left.\frac{d\sigma}{d\varepsilon}\right|_{\varepsilon,\, t} \tag{3}$$

Or the instantaneous derivative of the stress-strain curve at a specific strain level and time (Chua and Oyen, 2009). The resulted stress-strain diagram of the EPS under various loading rates are plotted in Fig. 3. The amount of the elastic modulus, failure stress and strain were also calculated and listed in Table 1.

2.2. Finite element model

A Three Dimensions (3D) FE model of the human skull was made via