7th Asia-Pacific Congress on Sports Technology, APCST 2015

Energy absorption and performance relevant to thermal wear comfort evaluation of existing impact protective pad and materials intended for impact protective pad

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Abstract

This paper reported an evaluation of the absorption energy and performance relevant to thermal wear comfort of existing hip protective pad and materials intended for use in hip protective pad. For energy absorption evaluation the experimental pads were compressed using Instron Tester, while dry thermal resistance and evaporative resistance of experimental pads were tested using sweating guarded hot plate. The stress-strain compression curves from the experimental results were used to analyze the absorption energy of the pads. It was determined that knitted spacer fabric had better relative energy absorption than closed cell foams, and better absolute energy absorption when treated with shear-thickening fluid. Also, the dead mass of spacer fabrics is the lower than the one of foams. Physical form and morphology of knitted spacer fabric allowed easier thermal and vapour transfer to the environment in comparison to those of closed-cell foam, where knitted spacer fabric had both lower dry thermal resistance and evaporative resistance values than closed cell foam which makes the knitted spacer fabric suitable for protective pads used in high sport activity and hot environmental environments. This study concluded that knitted spacer fabric could successfully be used as alternative material for impact protective pad.

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Peer-review under responsibility of the School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University

Keywords: Energy absorption; hip protective pad; knitted spacer fabric; design strain; dead mass

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1. Introduction

Impact protective garments are commonly worn by athletes in a variety of sports in which body contact with either another participant or a piece of equipment commonly occur, and present a risk of injury to the athlete [1]. In any contact sport where impact and collision is an accepted feature, the use of various forms of external padding has become common. Padding is most commonly seen as the use of any material with impact absorption qualities that is applied to vulnerable body parts to minimize the effects of direct contact. The different materials currently used in padding including various combinations of rubber, compressed foam, leather and industrial foam rubber [2].

Closed-cell structure foams are currently widely used for impact protection. Closed-cell foams in general come with a low moisture absorption coefficient and high thermal insulation and, compared to open-cell foams, a relatively heavy weight due to their higher density. These special characteristics of closed-cell foams and the fact that effective protective functionality requires a high degree of thickness and rigidity of the foam material potentially create serious comfort problems for the wearer [3]. In addition, tight and secure fit of a body protector, which is an essential requirement to counteract its displacement that can reduce the protective function [4,5], adversely affects the comfort of the wearer.

In recent years, applications of knitted spacer fabrics as substitutes for foam materials have attracted increasing attention [3]. Knitted spacer fabrics comprise two independent fabric layers connected by separate spacer yarns. The space between the two outer layers provides an open construction that allows sufficient airflow, enhancing heat and vapor transport away from the human body [6].

The thermal homeostasis of the body is a result of the balance between heat production and heat dissipation. The primary factors of importance for this balance are the energy metabolism, clothing thermal properties and ambient climatic conditions. Clothing effects on heat exchange are basically described by two properties: dry thermal resistance and evaporative resistance. Dry thermal resistance is the resistance to heat transfer by convection, radiation and conduction. Evaporative resistance is the resistance to heat transfer by evaporation. Evaporative resistance is a moisture transfer resistance, as the transferred heat is bound to moisture that evaporates at the skin surface and passes to the environment [7].

This paper focused on evaluation of the energy absorption and performance related to thermophysiological wear comfort of the existing impact protective pad and of the textile materials as alternative material for protective pad. This study investigated the influence of different materials suitable for protective pads on their energy absorption, thermal resistance and evaporative resistance.

2. Experimental

Seven existing commercially available materials were selected for the study (Table 1). Three of them were hip impact protective pads (A, B and C) and four experimental materials were intended for impact protection.

| No | Code | Material                                | Thickness (mm) |
|----|------|-----------------------------------------|----------------|
| 1  | A    | Polyurethane closed cell foam            | 16             |
| 2  | B    | Polyester knitted spacer fabric- 4 layers| 16             |
| 3  | C    | Polypropylene closed cell foam- segmented| 9              |
| 4  | D    | Polyurethane closed cell foam            | 6              |
| 5  | E    | Polyester knitted spacer fabric          | 7              |
| 6  | F    | Polyester knitted spacer fabric          | 6              |
| 7  | G    | Knitted spacer fabric treated with shear thickening fluid | 5 |

The samples were compression-tested with an Instron Tester Model 5565A at a crosshead speed of 500 mm/min. From the stress-strain curves, the maximal ratio of energy density \(W\) to stress \(\sigma\), incorrectly denoted as
efficiency, was calculated, and the maximal $W_{\text{max}}$, $\sigma_{\text{max}}$ and strain ($\epsilon_{\text{max}}$, design strain) were determined at this very ratio, according to the method of Fuss [8]. In addition to that, the dead mass (per unit volume) was determined from the density of the materials [8]. Four to eight samples were tested per model.

Dry thermal resistance and evaporative resistance of experimental pads were tested using MTNW sweating guarded hot plate. The equations used in calculations were as follows [9]:

Dry thermal resistance, $R_{\text{ct}}$ calculated for each zone by the formula:

$$R_{\text{ct}} = \frac{(T_{\text{skin}} - T_{\text{amb}})}{Q/A} \quad (1)$$

where : $R_{\text{ct}}$ = dry thermal resistance (m$^2$·°C)/W; $T_{\text{skin}}$=zone average temperature (°C); $T_{\text{amb}}$= Ambient temperature (°C) and $Q/A$= Area weighted Heat Flux (W/m$^2$)

Evaporative resistance, $R_{\text{et}}$ calculated for each zone by the formula:

$$R_{\text{et}} = \frac{(P_{\text{sat}} - P_{\text{amb}})}{Q/A} \quad (2)$$

where : $R_{\text{et}}$ = evaporative resistance (m$^2$·Pa)/W; $P_{\text{sat}}$=saturation pressure vapor at skin temperature (Pa); $P_{\text{amb}}$= ambient pressure vapour at ambient temperature (Pa) and $Q/A$= Area weighted Heat Flux (W/m$^2$)

Permeability Index ($I_m$) is commonly used to characterize the ability of water vapor to move through clothing which affects the amount of evaporative cooling that can occur as a result [10]:

$$I_m = K \cdot R_{\text{ct}}/R_{\text{et}} \quad (3)$$

where : $I_m$ = Permeability Index (Dimensionless); $R_{\text{ct}}$ = dry thermal resistance; $R_{\text{et}}$ = Evaporative resistance; $K$ = constant (60.6515 Pa/°C)

The permeability index $I_m$, takes the form of an efficiency factor. It has a theoretical range from 1 (for the ideally permeable system) to zero (for the completely impermeable one). It does not include thickness and it is also a dimensionless quantity, so that it has the same value regardless of the system of units used. Therefore, $I_m$, is a more satisfactory term by which to describe material moisture permeability than $R_{\text{et}}$, which increases with thickness of material or clothing and has different numerical values depending on the system of units used [10].

To determine the significance of difference between experimental pads, statistical analysis was carried out. One-way analysis of variance (ANOVA) test was conducted to determine the equality variance. The null hypothesis (H0) for the test was that all population means (level means) were the same. The alternative hypothesis was that one or more population means differ from the others.

3. Results and Discussion

3.1. Energy absorption, design strain and dead mass

The maximal ratio of energy density ($W$) to stress ($\sigma$) determines the highest energy absorption at the least force (stress), or, in other words, the onset of densification. Shock absorbers should not be loaded beyond this optimum point. The maximum admissible strain at this optimum point corresponds to the design strain). The dead mass, i.e. the density times the uncompressed fraction of the strain, is the mass of the material not used for energy absorption [8]. Materials E and F (spacer fabrics, exhibited the highest $W/\sigma$ ratio, twice as high than materials B and D (Figure 1a). Materials F and G1 had the highest design strain. Material F (spacer fabric) is therefore the best choice for impact absorption out of the seven materials tested; and material B was the worst one. Material G consisted of two sub-types with different mechanical properties, one subtype without negative modulus, and another with a negative modulus after an initial peak stress and before densification. The reason for these two subtypes could be different types or surface thickness of the shear-thickening fluids, with which the material was treated. In terms of absolute energy absorption (Figure 1b); materials G and D were the best ones. Interestingly, spacer fabrics (E, F, G), with the exception of material B, exhibited better energy absorption than foams at the same stress (Figure 1b). Material F,
identified as the best choice for impact absorption above, is still suitable, but only at small impact stresses. At higher ones, material G1 is leading. Materials E and F had the smallest dead mass, and this as the highest $W/\sigma$ ratio (Figure 2). The trend that the smaller the dead mass, the higher is the $W/\sigma$ ratio was already described by Fuss [8].

![Graph showing maximal ratio ($W/\sigma$)$_{\text{max}}$ of energy density ($W$) to stress ($\sigma$) against maximal admissible design strain ($\varepsilon_{\text{max}}$); (b): maximal energy density ($W_{\text{max}}$) against maximal stress ($\sigma_{\text{max}}$); the material code used (A-G) corresponds to Table 1; G1 and G2 are the same material but with different mechanical properties.](image1)

![Graph showing maximal ratio ($W/\sigma$)$_{\text{max}}$ of energy density ($W$) to stress ($\sigma$) against the dead mass](image2)
3.2. Dry thermal resistance and evaporative resistance

The results demonstrate that the experimental pads had significantly different dry thermal resistance and evaporative resistance values (Figures 3.a and 3.b). It could be seen that pads A and B of the same thickness, had the same dry thermal resistance, however they had different evaporative resistance. For sport with high activity levels and high environmental temperatures, protective pads which have both low dry thermal resistance and evaporative resistance are preferable. Pad B had better ability to transfer vapour to the environment in comparison to pad A. Pads E, F and G made of spacer fabrics had both lower dry thermal resistance and evaporative resistance in comparison to the pad D made of closed cell foam. Pads D, E, F and G had very similar thickness.

From Figure 4 it could be seen that experimental pads had different permeability index values. Experimental pads E, F and G made of knitted spacer fabric each had higher permeability index than those of the experimental closed cell foam pads. This means that knitted spacer fabrics had higher ability to transfer heat and water vapor to the environment in comparison to the closed cell foams.
4. Conclusion

The findings of this study characterize the energy absorption values, dry thermal resistance and evaporative resistance of protective pads and materials intended for the fabrication of protective pads. From experimental results, it was found that knitted spacer fabrics could be successfully used as alternative materials for impact protective pads. Physical form and morphology of knitted spacer fabric allows the easy thermal and moisture transfer to the environment in comparison to closed-cell foams. Experimental knitted spacer fabrics had both lower dry thermal resistance and evaporative resistance values in comparison to the experimental closed cell foams that make the knitted spacer fabric more comfortable for the fabrication of impact protective pads for sport applications with high activity level and high environmental temperatures. These results are of significance for design and engineering of impact protective sportswear.

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