Journal of Manufacturing Systems 49 (2018) 61–74

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

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

A systematic pattern generation system for manufacturing customized seamless multi-layer female soft body armour through dome-formation (moulding) techniques using 3D warp interlock fabrics

Mulat Alubel Abtew[a,b,c,d,*], Pascal Bruniaux[b,c], François Boussu[b,c], Carmen Loghin[a], Irina Cristian[a], Yan Chen[d], Lichuan Wang[d]

[a] Faculty of Textiles, Leather and Industrial Management, 'Gheorghe Asachi' Technical University of Iasi, 53, D. Mangeron Blv., 700050, Iasi, Romania
[b] University of Lille Nord de France, Lille, France
[c] Ecole Nationale Supérieure des Arts et Industries Textiles (ENSAIT), GEMTEX, 2 allée Louise et Victor Champier, 59056, Roubaix Cedex 1, France
[d] College of Textile and Clothing Engineering, Soochow University, 178 G.J. D. Road, Suzhou, 215021, China

ARTICLE INFO

Keywords:
Computer-aided design
Multi-layer pattern generation
High-performance fibre
Seamless female soft body armour manufacturing
3D warp interlock fabrics
Dome-formation

ABSTRACT

Female participants in different perilous tasks including law enforcement offices have been considerably increased in the last few decades. However, they mostly wear men's body armour with smaller sizes which brings a negative upshot not only in ballistic protection performance, comfort, fitness but also in a psychological point of view. Hence, manufacturing female soft body armour based on their unique morphological differences for better ballistic protection without conceding fitness and comfort are in great demand. This research work presented a novel method using a systematic 3D design approach through parametrization process to generate block patterns for manufacturing successive layer in the panels. The deformable mesh on the 3D virtual adaptive female model was developed with grading values of zero. Parametrization process based on the thickness of each layer in the 3D design database was applied to generate the different successive meshes on the virtual mannequin with appropriate coordinates. Later, the multi-layers mesh developed on the virtual 3D female body has been flattened to acquire the different layer's pattern. Due to its excellent mouldability behaviour, 3D warp interlock fabrics made of high-performance fibre has been designed and developed to manufacture the seamless female body armour with a dome-formation process. The manufactured multi-layer panels were draped on the standard female physical mannequin for experimental validations. The result shows that the new 3D design approach and its manufacturing system was found easy and precise to generate the different multi-layer panels pattern for developing seamless female soft body armour.

1. Introduction

Ballistic protective body armour is one of the most important items used as police and military equipment in battlefields as well as the civilian subjected to fragments of materials for last many decades [1,2]. Different countries law enforcement agencies even have made it mandatory for their officers to wear ballistic vests while on duty. However, as suggested by many users, apart from ballistic resistance performances, the vests weight, comfort and fitness are extremely important due to the fact that, officers wearing a heavy and inflexible vest for long hours could be suffered by the generated excessive heat and its rigidity [3,4]. In the last few decades, thanks to researchers and armour developers, better light weighted and flexible soft body armour along with good ballistic performances has been greatly increased considering different parameters such as selection and improvement of appropriate materials (fiber), type and methods of fabric construction, armour component arrangement, and garment design techniques [5–7]. Still, efforts have been continued by the field scientists and researchers to develop better ballistic protective soft body armour with much-reduced weight along with better fitness and comfort.

Female participation in the field of law enforcement, privet security and military forces have been also significantly increased across the world [8,9]. This brings uniquely designed and manufactured female soft body armour becomes very vital due to their unique morphological shape than male personnel's. However, for the last many decades, surprisingly female officers were fitted with small sized male-based

* Corresponding author at: Faculty of Textiles, Leather and Industrial Management, 'Gheorghe Asachi' Technical University of Iasi, 53, D. Mangeron Blv., 700050, Iasi, Romania.
E-mail address: mulat-alubel.abtew@ensait.fr (M.A. Abtew).

https://doi.org/10.1016/j.jmsy.2018.09.001
Received 12 June 2018; Received in revised form 12 August 2018; Accepted 11 September 2018

body armour systems which definitely not acceptable not only physiological differences but also impose disproportionate on fitness, comfort, and bad ballistic protection. After considering the differences body shapes among male and female, different study has come out with solutions to reduce such problem based on designing techniques and proper material selection [3,10–18].

Concerning the female body armour design approach, the common traditional design techniques such as cut-and-sew, fabric folding, and overlapping were usually used to form the curvilinear shape and to accommodate the bust area. Even though those methods had their own drawbacks, they are far better as compared to the unisex body armour design in bringing fitness and comfort. For the last many years, the most commonly and widely used design approach in industry is a cut-and-sew method by involving different dart designs to accommodate the bust area. However, the stitches on the dart seam line also creates the weakest point against projectile impact which ultimately reduces the ballistic performance of material [19]. Fabric folding is also barely used female body armour designing techniques through dome-formation [3,20]. This technique used to shape the materials into three-dimensional form by folding the materials and stitched at the side in a certain shift. This also revealed the limitation of ballistic performance due to material discontinuities and weak stitching area around folded material. Besides, many folded fabrics at the side with sharp edges create thicker panels while folding which causes itching, less personal mobility and discomfort. Another method is creating superposed layers of ballistic material layers to develop front protective panel contoured called overlapping. Although using overlapping seams are much stronger in fabric stitching; however, the small ballistic missiles still can penetrating by severing the loop of threads among the seams [21,11].

In general, apart from designing, the above methods also face a problem of obtaining an accurate surface data for women's breasts due to its ambiguous borderline with the skin surface. This indicated that still developing female body armour frontal panel which properly accommodates the bust area with better impact performance, comfort and fitness for different women morphology without the need of cutting, stitching, stretch folding or folding is very imperative. Currently, the most commonly used designing technique to avoid the above problem is moulding. This developing method usually creates the required 3D shape through dome-formation once the intended shape is defined. Moreover, it is also known that female soft body armour should be adaptive to the required human body morphology in order to ensure the effectiveness of the ballistic protection. This leads as the ballistic vest resemble the required shape of the body, the better the fitness and efficient protection will be obtained. While designing female body armour panel using moulding method, it is possible to create seamless frontal front by mimicking the bust area without the need of cut-and-stitch or any other finishing methods. Due to this, it ultimately gives better comfort, fitness and better ballistic protection than any other design methods. However, unless properly applied, the methods might also create shear deformation, panel thickness variations, and wrinkles on the material and body size limitations.

Various researchers have been and still working hard to solve the above-mentioned limitations of female soft body armour through different pattern designing approaches and comprising proper material selections. One of the researches applied a three-dimensional (3D) moulded multi-layer laminated woven structure to developed female body armour for ballistic protection through better retaining and conforms to the female torso. The moulded shape was sustained using a thermoplastic material to infuse the fibre of the three-dimensional woven material to each other. The designed were also claimed for providing increased comfort and ease of movement when the protective wear is in use [12]. Nowadays, 3D design process, a recent technology applied in the clothing industry, helps companies to meet the challenges posed by the market, in terms of new product development processes including soft body armour. Even if the development of virtual custom models is a challenging process, is a very important accompaniment to the field "ready to wear" and mass customization, crucial to direct garment design in the 3D world [22,23]. The researcher also approach to 3D prototyping process in corsetry design employing the scanning process and it leads to woman chest separated from the body and parameterized, that can be adopted individually in a relationship of given customer's morphology. Another interesting research tried to optimized the protection zones and use of a virtual body given by the body scanner to make a tailor-made bullet-proof vest with more comfort and can improve the measurement process to accelerate the sizing process [24]. Similarly, another research has also used a three-dimensional design process for female body armour using the darts rotation technique, which can indeed improve the traditional two-dimensional design process by providing a comparatively precise fit to satisfy female morphology. The key technique here is to form the three dimensional shape by providing many darts and stitches to two-dimensional flat fabric, such as plain weave-structure fabric, but it is not suitable for three dimensional weave-structure fabric, such as angle-interlock woven fabric, which is already capable of shaping deep dome designs without darts or other assistance, due to its unique property of high mouldability. A new approach has been also proposed to better introduce the different personal parameters of the body inside the new geometric definition of the vest. The optimization of the protection zones of the global vest and the assembly process leads to a reduction of weight and contribute to a reduction of the waste quantity during the cutting operation. The achievement of a gradient protection at the chest level helps also to avoid a failure in the protection like done with the shearing stress. Afterwards, it can be possible to create a base virtual dummy with scalable measurements, depending on a certain number of measures in order to recreate the internal surface of the bullet-proof vest. The use of a virtual body given by the Body Scanner to make a tailor-made bullet-proof vest to more comfort can improve the measurement process to accelerate the sizing process [25]. Seamless knitting technology along with CAD software was used to design a three-dimensional seamless female body armour vest both in bra-vest and loose-vest design style. However, not only knitted fabrics might give poor ballistic protection but also while designing the multi-layered panel size was increased randomly for each additional layer by using half-ease allowances in the width and length which can later affect the fitness [26]. Another study also develops parametric design methods for generating human body models of varying size according to different anthropometric measurements in the 3D domain, which is the basis of style design and 3D presentation for warp-knitted seamless garments [27]. A mathematical modelling has been also presented to determine the flatten pattern geometry for the single layer front panel of female body armour by considering both body and bra size as the input with satisfactory ballistic performance in speedy pattern development way [19]. The methods have divided the bust area into seven different parts by using the simplest surfaces. It also investigates different models with different shapes considering accommodating the bust volume. In this research in order to find a more realistic model, the study tried to develop and investigate the models with different shapes considering accommodating the bust volume. Meanwhile, in order to develop the pattern making methods which are simpler but sophisticated with better fabric consumption and distribution on the body surface mainly by considering the shape of the bust on the mannequin. Later, in continuation of this work, based on this mathematical model, patterns for different layers of fabric for the whole panel were developed considering the relationship between the thickness of the fabric and the pattern block projection [28]. The study also uses an angle-interlock woven fabric due to its mouldability and satisfactory ballistic performance for developing female body armour with dome shapes. Even though the result shows a satisfactory result for the given body size, however, the methods used the traditional bra sizing system which may still bring fitness problem on the wearer. Moreover while flattening; the deformational stress on the fabrics might not be uniform throughout the front panel. This might have a problem on the final ballistic