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Towards a mean body for apparel design ☆

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ABSTRACT

This paper focuses on shape average with applications to the apparel industry. Apparel industry uses a consensus sizing system; its major concern is to fit most of the population into it. Since anthropometric measures do not grow linearly, it is important to find prototypes to accurately represent each size. This is done using random compact mean sets, obtained from a cloud of 3D points given by a scanner and applying to the sample a previous definition of mean set. Additionally, two approaches to define confidence sets are introduced. The methodology is applied to data obtained from a real anthropometric survey.

1. Introduction

Shape analysis is an important topic in many scientific fields such as Biology, Archaeology, Medicine, Geology and, in recent decades, also Computer Vision. Many image processing tasks need some way to average different shapes. Three major approaches can be identified in Shape Analysis, based on how the object's shape is treated in mathematical terms [34]. Shapes can be treated as sequences of points (landmarks), as compact sets on $\mathbb{R}^m$, or they can be described using functions representing their contour. The main aim of this work is to obtain averages of shapes together with their confidence sets by considering the shape of any object as a compact set on $\mathbb{R}^3$. Finally, these averages and their associated confidence sets will be used to define prototypes for the apparel industry.

We have to note that the theory of random compact sets provides a more general framework. For example, a simple random set is obtained as an unordered collection of random points $X = \{x_1, \ldots, x_k\}$. These k points can be interpreted as landmarks; if a specific order of them is prescribed.

Anthropometric data provide fundamental information to the apparel industry. Designers and pattern makers would like to have mannequins that represent the main anthropometry of a basic size, which can then be scaled proportionally to cover most of the population.

The primary anthropometric information used by clothing designers consists of tables that list the mean values of the main anthropometric measurements for each size. Most of this information has been developed from the designers' own experience or has been based on a beauty canon that is far from the real shape [18].

Nowadays, the technical design of a garment is still a handcraft job that requires several trial and error tests in order to achieve the patterns of the garment with a good fitting and style. The starting point of a pattern maker to develop a new garment is a basic pattern block that has key features similar to the new garment. This basic block is generated according to a set of body measurements that ranges from 15 to 20 representing an ideal canon of body proportions for the standard size established by the company [21]. The set of body measurements of the standard size is scaled to other sizes creating the 'sizing tables' which are the anthropometric references of companies and pattern makers to develop new garments and the range of sizes [3]. Each company has their own sizing tables that are confidential information not shared by the clothing sector. Using the patterns of the basic block a prototype of the garment is manufactured in order to check it with 'life models'. They are subjects

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with body dimensions close to the values of the standard size. During the fitting tests, the prototype is manually adjusted including references to develop the updated patterns. Depending on the garment complexity, these manual trials should be repeated between two and four times in order to achieve the definitive patterns, being a significant economic burden for companies [4]. In addition, the body dimensions of the 'sizing tables' used as a reference by pattern makers are based on old data refined after many years of practice. Therefore, the fitting of the new developed garments is not for body proportions of the real population. There is a lack of standards in the clothing industry representing the body dimensions and shapes of the real population worldwide segmented by sizes.

In recent years, emerging technologies for body scanning and user's fit problems, together with mass production of clothing, have promoted new sizing surveys to update the anthropometric data of the population in different countries [28]. So far, most of the research studies performed [1,10,36] focus on the analysis of these data for their application in apparel design [11,19,31,35].

The extended use of computer-aided design promotes the development of many tools that use information from anthropometric measurements to create virtual 3D models of humans that can be added to any virtual environment or workspace [16]. There are two types of 3D human body models: digital human models (DHM) and avatars.

DHM are parametric body models, which simulate body proportions, postures, reach ranges and motions [9,37] based on anthropometric data and regressions.

In the case of avatars, the main objective is to provide a realistic visual representation. They give priority to an aesthetic appearance, leading to unreal 3D body shapes. Besides, deformation methods that are not based on statistical distributions are used.

In this context, different authors have analyzed human shape variability using a landmark or dense surface-mesh representation of 3D human bodies. A set of 3D points are taken on the body surface, chosen either by their significance (anatomical landmarks) or by their positions (for instance, nodes on a projected 2D mesh). Their coordinates are organized as a vector of data where each component is taken as a variable. A principal component analysis (PCA) is applied to these data, retaining only the components which account for a certain amount of the total variability [6,29,39]. Some statistical summaries of these PCA-transformed data can be taken as descriptors that can efficiently represent the human body shape and size at different levels of detail; this is an area still under research [37].

In contrast to these approaches, in this work we present a new statistical methodology to define prototypes based on 3D point clouds corresponding to 3D scans. Using these 3D datasets provided by the scanner, we will obtain a 3D binary image, i.e., a 3D shape. The sample of 3D binary images can be considered as a random sample of a random compact set in $\mathbb{R}^3$. From this point of view, we propose to average them using the concept of mean set. Additionally, confidence sets, which are regions containing the corresponding mean with a certain level of confidence, are also calculated.

A random compact set is a natural probabilistic model for shapes. The formal definition and examples can be found in [26,34] and [13], among others. There is no single definition of mean set and different definitions can be found in the literature, like the Aumann mean [2,5], the Vorob'ev mean [33,38] and the Baddeley–Molchanov mean [7]. Of these definitions, the Baddeley–Molchanov mean is, perhaps, the most flexible because different results can be obtained by using different metrics in such a way that the distance is chosen by taking into account a specific application. Additionally, the Baddeley–Molchanov mean can be defined for general compact sets, whereas the Aumann mean is only suitable for convex and compact sets. Furthermore, the Vorob'ev mean is applicable to non-convex sets but is not suitable for random sets with null volume. In our application, we are dealing with non-convex sets and the Aumann mean should not be applied. The Baddeley–Molchanov and Vorob'ev means can be used because our sets have a positive area. Initially both definitions were applied, but the in-depth study was performed with the Baddeley–Molchanov mean. In the 2D case [15] the Vorob'ev mean provided very poor results. However, a preliminary evaluation for this 3D case shows a better performance than in the 2D case but with slightly coarser shapes than the Baddeley–Molchanov approach. The Baddeley mean is the best option for our problem. As it is well known, the Vorob'ev mean is sensitive to misregistration or displacement of thin features and this can easily happen in the problem that concerns us. In our opinion, this is why the Vorobe'ev means obtained are coarser than the Baddeley–Molchanov means.

The proposed method will be applied to the 3D anthropometric survey of the Spanish female population.

The outline of the paper is as follows. The definition of random compact set and the Baddeley–Molchanov mean are briefly reviewed in Section 2. Confidence sets for the mean sets are discussed in Section 3. Section 4 contains the results of applying our methodology to the anthropometric database of Spanish women. The paper ends with some conclusions and further work in Section 5.

2. Mean sets

Let $\mathbb{R}^3$ be the 3D Euclidean space and let $\mathcal{K}'$ be the collection of all non-empty compact subsets of $\mathbb{R}^3$. A random compact set, Φ, is defined as a measurable function from a probability space $(\Omega, \Sigma, \mathcal{P})$ into $(\mathcal{K}', \mathcal{B}(\mathcal{K}'))$, where $\mathcal{B}(\mathcal{K}')$ is the Borel σ-algebra of $\mathcal{K}'$ generated by the myopic topology.

The myopic topology on $\mathcal{K}'$ has the sub-base that consists of

$$\mathcal{K}^F = \{K \in \mathcal{K}' : K \bigcap F = \emptyset\}, F \in \mathcal{F}$$

and

$$\mathcal{K}^G = \{K \in \mathcal{K}' : K \bigcap G = \emptyset\}, G \in \mathcal{G},$$

where $\mathcal{F}$ and $\mathcal{G}$ denote the family of all closed and open subsets of $\mathbb{R}^3$, respectively.

The formal definition with theoretical properties and applications of this concept can be found in [13,26,34] and [27] among others. From now on, let us denote by Φ_i the shape corresponding to the i-th woman (in fact, her torso), with $i = 1, \ldots, n$, which will be considered as a realization of a random compact set in $\mathbb{R}^3$, Φ.

Unlike the uniqueness of the definition of the expectation of a real-valued random variable, the random sets have different features and so particular definitions of expectations highlight particular features which are important in the chosen context (see [27]). That is why different definitions of the mean set of a random compact set can be found in the literature; three of them are particularly relevant: the Aumann mean [33], the Vorob'ev mean [33] and the Baddeley–Molchanov mean [7]. Each of these definitions of mean set is based on the average of a certain random function associated with the random set. The Aumann mean is based on the *support function* of the set, the Vorob'ev mean on the *coverage function* and the Baddeley–Molchanov on a *distance function*. Other recent definitions of mean set can be found in [32] and in [22].

2.1. Baddeley–Molchanov mean set

First, some basic notation will be introduced. Let Φ be a random compact set on $\mathbb{R}^3$ and $\mathcal{K}'$ the space of non-empty compact subsets