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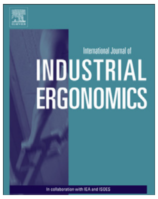

A new data structure and workflow for using 3D anthropometry in the design of wearable products

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ABSTRACT

The human body is a complex biomechanical system that exhibits many variations. Wearable products should be both functional and comfortable. They require a close and accurate fit to the body of the end-user. Current approaches to design body near products rely on 1D anthropometry and unrealistic manikins, e.g. constructed from simple surfaces such as spheres and cylinders connected by splines. With the uprising of 3D scanning, a myriad of accurate 3D body models becomes available. In this paper we present a framework to use this 3D shape information in the development of wearable products. The key concept that we introduce to achieve this extension, is an enriched shape model: a statistical shape model of the human body that also contains all 1D anthropometric data in it. With enriched shape models, a 3D shape can be parameterized with a given set of anthropometric features. Thus the dense geometric information of an individual's shape can be obtained simply by tuning that individual's anthropometric values. By designing on the generated 3D surface, a product can be obtained that closely fits the individual's shape. We thus extend the method of linking 1D anthropometric data with the dimensions of a product. This results in three design strategies that link both body shape with product geometry: design for collective fit, design for fit within clusters and design for individual fit. Each strategy is explained and studied with the design of wearable EEG headsets that fits the human head.

Relevance to design practice

We present a workflow to use accurate 3D shape models of the human body in the design of products that should closely fit the end-user. To that end, we introduce enriched shape models: a new data structure that contains all dense geometric shape information together with classical anthropometric data. We illustrate how enriched shape models can be used to achieve products with personalized fit, as an extension to the use of univariate anthropometric data. The use of enriched shape models for personalized design could become an important driver for mass customization. To that end, tools and techniques should be developed to incorporate the presented workflow in CAD/CAM.

1. Introduction

Anthropometry is used in the process of industrial design to cope with variations between humans with the aim to optimize products for fit, comfort, functionality and safety (Pheasant and Haslegrave, 2016). The human body exhibits many variations, both in size and in shape. Consumer products that have a close fit with the human body often require full 3D models of the human body or body parts.

Companies that develop head mounted products such as helmets, headgear, glasses and headphones are interested in new tools and techniques to incorporate realistic and accurate head models in their design process (Ball, 2009; Luximon et al., 2016; Chu et al., 2015). Also in the design of protective clothes and safety equipment, sports equipment, and for the development of medical and orthopedic products, there is a need for accurate descriptions of the shape variations of the human body (Alemany et al.; Wang and He, 2013; Baek and Lee, 2016; Van Tongel et al., 2014). These efforts and

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needs show that the sparse geometric information contained in 1D anthropometric data is not adequate enough to ensure proper fit, comfort and functionality.

With 3D scanning, dense and detailed geometric information of the human body can be captured. Technological advances in image capturing devices (e.g. 3D scans, cameras, computercam, Kinect, smartphone), medical imaging (CT and MRI scans), image processing software (Zhang et al., 2013), allow for construction large databases of 3D body shapes. Realistic static 3D images of the human body are increasingly available over the past decade (Robinette et al., 1999) (Robinette et al., 2002) (Ball et al., 2010). With the alignment of international 3D anthropometrical databases (Triess et al., 2013), a realm of realistic 3D models of the human body is potentially constructed (Ballester et al., 2014). Data acquisition is regulated by ISO 20685:2010. This norm can be targeted by convenient 3D scanners (Pesce et al., 2015), so the amount of 3D data is expected to increase even further. 3D anthropometry is an emerging field with great potential for industrial design (Niu and Li, 2012). Accurate 3D body data in digital form might be useful for optimizing product comfort and function (Niu et al., 2009). The merits of new tools to deploy true body models directly in the process of industrial design are clearly demonstrated (Luximon et al., 2016). For the moment, they are confined to one specific design on one specific manikin. The question arises how parameterized designs can be constructed that directly adapts to a subjects 3D anthropometry, in an intuitive, smart and efficient way.

The purpose of this paper is to present a data structure that contains the full geometric complexity, intrinsic organic nature (variable radii of curvature) and variation in human body shape and that allows a practical and user-friendly workflow for the design of wearable products. In the next section (Section 2) we present three design strategies that link 1D anthropometric data with product dimensions: design for collective fit, design for fit within clusters and design for individual fit. The aim of each strategy is to define products whose dimensions are aligned the dimensions of the target population. Then, in Section 3, we explain how each of these three strategies can be extended to a new design strategy. The three new design strategies link accurate 3D models of the human shape with the entire product surface geometry, to achieve a fit between product and surface shape.

Digital design tools have been developed to apply these new design strategies on the human head. In Section 4 we present three design cases as a proof of concept for each design strategy. The human head is particularly suited to study these new workflows, because of its relevance in industrial design practice and the static, geometric nature (Luximon et al., 2016). Results are discussed in Section 5 and concluded in Section 6.

2. Linking body sizes to product sizes

Traditional 1D anthropometrical data are numbers that represent body dimensions. Their statistical distribution is univariate, by definition. It is straightforward to link such data on human sizes with the dimensions of a product, or vice versa (Siemenssoftware, 2011; Garneau and Parkinson, 2011; Molenbroek and de Bruin, 2005).

There are established and straightforward design strategies for applying 1D anthropometry in the design process to take account of that variation throughout the target population. These design strategies all exploit the fact that direct relations can be defined between product dimensions and body parameters and are well integrated in the design process (Molenbroek and de Bruin, 2005; McGinley and Dong, 2011). The univariate character of 1D anthropometric data ensures that it can be linked to product dimensions. The fact that these data represent physical parameters ensures that they can be retrieved in a practical life context. Consequently, design strategies can be defined to determine proper product size. The first strategy is a design for collective fit or design for the average (Steinfeld and Maisel, 2012), or a design for all, where a single solution is adapted such that it is usable for the whole population (Marshall et al., 2010). The second strategy is a design for fit within cluster strategy that is derived from achieving fit by considering percentiles (Pheasant and Haslegrave, 2016) and overlaps of percentiles. The last strategy is an approach where the design is tailored to a subject's individual sizes.

2.1. Design for collective fit

A first design strategy that we consider is *design for collective fit*. The dimensions of a new product are pinpointed such that only one product size can fit the entire target population. Often, mean, median, percentiles or extreme measures are relevant parameters for a design base in this approach. Variations throughout the target population are coped within the design, e.g. by material characteristics, such as flexible temples to achieve universal fitting sunglasses, or by adjustable elements e.g. (universally fitting) folding bike optimization (Sun et al., 2013). A contemporary example is the design of a bicycle that can be shared (DeMaio, 2003, 2009), meeting trends and opportunities for improved and cleaner traffic (DeMaio, 2009; Shaheen et al., 2010).

This design strategy potentially yields a sub-optimal fit for some subgroups.

2.2. Design for fit within clusters

A second strategy is to *design for fit within clusters*. Thereby the domain of the target population is clustered to minimize variation in size in each part. The design problem to achieve proper fit is thus reduced to finding a proper fitting design for each cluster. Each subproblem is thus equivalent to a design for collective fit for the target population restricted to the respective cluster. Cluster specific measures such as cluster mean, -median and −extremes are relevant parameters for a design base in this approach.

For example, for the purpose of bicycle design, the domain of the target population is usually first split up along gender (m/f). This first variability is coped with offering different designs for men and women. Then populations are clustered and frame sizing systems are defined according to the developers experience and available information (Ulrich et al., 1997; Hsiao, 2015).

2.3. Design for individual fit

A third design strategy is to *design for individual fit.* This means that the dimension of the product are completely tuned to the individual sizes of one particular end user. If 1D body data is directly connected to the dimension of a product, it suffices to alter the dimensions accordingly to achive an individual fit. Such examples can be found in personalized bike fitting, e.g. to achieve maximal comfort (Zhang et al., 2015).

3. Enriched statistical shape models: from 1D to 3D anthropometry

A statistical shape model (SSM) is a collection of similar forms in which each form is described with a common parameter domain. For each shape, this is a one-to-one parameterization such that a correspondence between similar points is established (Dryden and Mardia, 1998; Heimann and Meinzer, 2009). Research on statistical shape models of the human body has made major progress, with over the last decades the seminal work of Allen to establish