Methodology for Design of Well Fitting Load-Bearing Belts

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https://doi.org/10.15221/24.36

Abstract

Rapid advances in scanning technology have revolutionized the ability to accurately reproduce the contours of scanned objects, facilitating the design process for various product categories. In the apparel industry, these systems are particularly effective in creating custom-fit garments tailored to individual customers. However, for mass production, it is necessary to generalize and interpret the scan data to establish standard size categories that represent typical consumer groups. At the same time, some products manufactured within this framework can only achieve their functionality if they smoothly fit to the human body. An illustrative example would be a carrying system whose main function is to distribute weight between the shoulders and hips. The effectiveness of this load distribution is directly influenced by the contact area between the belt and the body: the larger the contact area, the lower the perceived load. This principle can be applied to various load-bearing products such as backpacks, functional harnesses such as tactical harnesses and mounting harnesses as well as baby carriers.

The goal of our research is to develop and test a methodology for the design of function-specific mass-produced items that closely conform to the surface of the lower body, using functionally specific harness systems with tool bearing belts or assembly belts as a case study. For this purpose, parametric human models in standard sizes (e.g. German women's sizes 38 to 54) with three hip width variants - narrow, normal and wide - were used, which were previously developed for 3D product design projects. These models served as a prerequisite to investigate the typical geometry of the lower body surface. The area of interest was limited to the area between waist and hip circumference, as recommended for optimal belt positioning on the body. The 3D construction of the functional belt is carried out directly on the parametric human model in the Design Concept 3D software, Lectra. The 2D pattern parts are automatically unfolded from the 3D design. These flattened patterns were analyzed and standardized, taking into account the body geometry of the different sizes, the material properties and the subsequent manufacturing processes. The anthropometric fit of these designs was verified through simulations in 3D garment design software. This approach ensures that the resulting products not only meet the requirements of mass production, but also provide the necessary functionality and comfort for the end user.

Keywords: body scanning, pressure distribution, load-bearing system, anthropometric fit

1. Introduction

In the design of functional clothing, the geometry of the human body represents a crucial determining factor in ensuring its effective utilisation in the intended functional conditions. It is of particular importance to consider the anthropometric surface to which the product is directly aligned. For example, for the upper body clothing, this is the upper supporting surface, which is limited to the acromion, thoracic and scapular anthropometric points. In the case of waistwear, the lower supporting surface commences at the waist and is delineated at the inferior limit by abdomen, high hip, and buttock landmarks. The balanced fit of the product to the supporting surfaces ensures its aesthetic appearance, comfort, and, consequently, a high level of quality.

In the case of close-fitting garments, the human body contact surface must be perfectly aligned with the product geometry. Inconsistencies in these two surfaces can be compensated for by the elasticity of the materials or adjustable components [1]. In the case of therapeutic or rehabilitative products, where the desired therapeutic effect is achieved through compression, a user-centered design approach is of paramount importance, ensuring that all anatomical features are clearly considered in the product development process [2].

The aforementioned examples serve to illustrate the significance of a comprehensive and detailed consideration of the contact surface of the garment with the human body throughout the design process. Conventional methods of garment design, based on the initial data obtained from standard figure measurement charts, are effective in reproducing body sizes, but less successful in replicating body shapes. It is frequently the case that differences in shape within a given size are taken into account in the form of additional characteristics, such as figure type, posture, body morphology, and so forth. Nevertheless, this introduces an additional layer of complexity to the production of mass-market consumer goods within the established system of standardised sizes.

The advent of modern digital technologies, including body surface scanning, the creation of interactive digital tweens, and virtual simulation of products, has the potential to enhance and, in certain instances, supplant traditional methodologies. To illustrate, three-dimensional (3D) scanning represents a sophisticated technique for digitally reproducing the human body or specific body parts. As the resulting scans are essentially point clouds that can subsequently be converted into a triangulated surface by appropriate processing, they provide a basis for a variety of automated processes. The resulting scans can be employed as a basis for the extraction of anthropometric measurements, which will then be utilised as input for the design process [3]. An alternative method is to obtain flattened planar faces [4]. Four-dimensional (4D) scanning represents the latest and most advanced stage in the development of scanning technologies. Four-dimensional scanning technology enables the capturing of alterations in the human body's surface over time, with the body assuming a range of poses. Sensitive cameras capture the position of the body surface with high speed, and the software is capable of reproducing it with high resolution. This enables the utilisation of dynamic measurements and the optimisation of garment design, taking into account the aforementioned dynamic effects [5].

As a consequence of the authors' previous research into the design of belt systems for the transportation of objects [6], the necessity for the current study was established. In the context of load transportation, the area of contact between the system and the body represents a pivotal factor, both in terms of functionality and in the reduction of the risk of stress-related illness and injury. An optimal fit, characterised by close and uniform contact between garment and body, enables an even distribution of the load across the surface area, thereby preventing its concentration in specific areas.

In the case of the lower body surface, the lack of clear guidelines regarding the dimensional characteristics of this surface presents a significant challenge in the design of products with a tight fit. Designing products for the female consumer presents particular challenges. The women's group of products is particularly problematic, as women's figures have greater variability in the waist area compared to men's. A literature review reveals several solutions for the design of underwear, trousers, and hygiene products [7, 8]. Nevertheless, these studies cannot be employed for the design of belts since they focused primarily on the ergonomic component and were based on standard body measurements.

In light of these considerations, the objective of our research was to examine the lower supporting surface of women's figures to establish the fundamental data for the design of tight-fitting belts and to identify the optimal number of sizes required to encompass the fullest possible range of female figures.

2. Method

2.1. Development of parametric human models

The initial step in the development of 3D-based belt systems is the creation of virtual human body forms that facilitate size- and figure-specific scaling.

The size classification system for the apparel industry, Size Germany, categorises women's figures into 15 sizes from 32 to 60, three heights (short, normal, long), and three body shapes (slim, normal, wide). In the present study, the size range was limited to include medium-sized figures of 38-54 with different body shapes. The aforementioned three types of figures are further specified by the corresponding letters, as follows: S-slim, N-normal, W-wide.

The initial reference point is provided by average body forms in sizes 38, 42, 46, 50 and 54, which were developed from scan data. The data were available in the form of triangulated surfaces and, as a result, were unsuitable for automatic scaling and constructive applications in CAD systems. In order to achieve this, it was necessary to generate spline surfaces from a defined number of sections. The points on the body used to determine the body measurement lines (e.g., bust, waist circumference, etc.) or the measurement distances (e.g., shoulder width, etc.) were used to position the cutting planes. The points of intersection of these lines were stored in a database in the form of x, y, z coordinates for size-specific scaling, thereby enabling automatic scaling (Figure 1). The figurines were developed as part of the research project 18223 BG / 2.

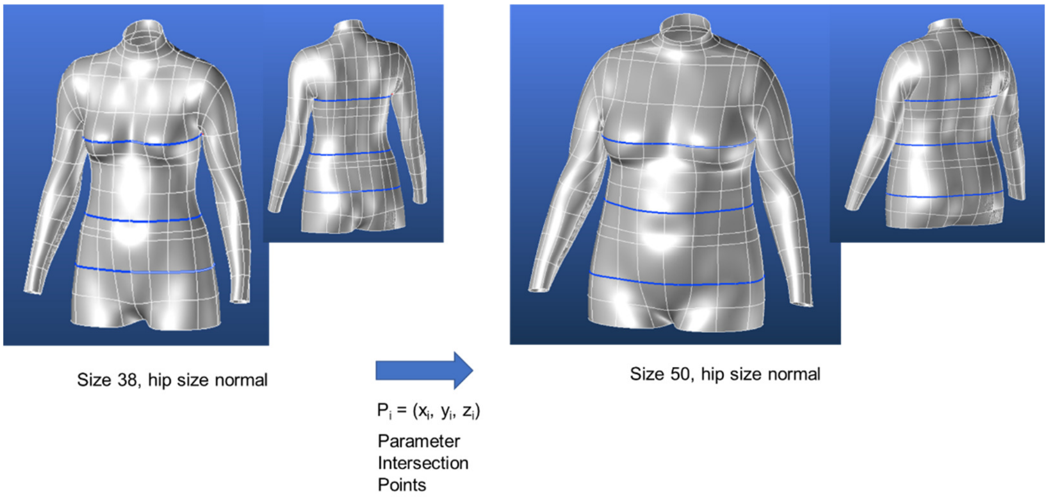

Fig. 1. Size-specific scaling of generated spline surfaces.

2.2. 3D garment pattern design

The 3D design of the belt was created using the virtual parametric human models that had been obtained. To achieve precise adjustments and secure placement of the belt on the virtual body, the belt shape was described using free-form surfaces, which were created based on style-relevant lines. The geometry of the belt pattern was generated from both the waist and hip circumferences as a style line (Figure 2). The parametric figurines and the 3D belt pattern design were created using three-dimensional computer-aided design software, specifically Lectra Design Concept.

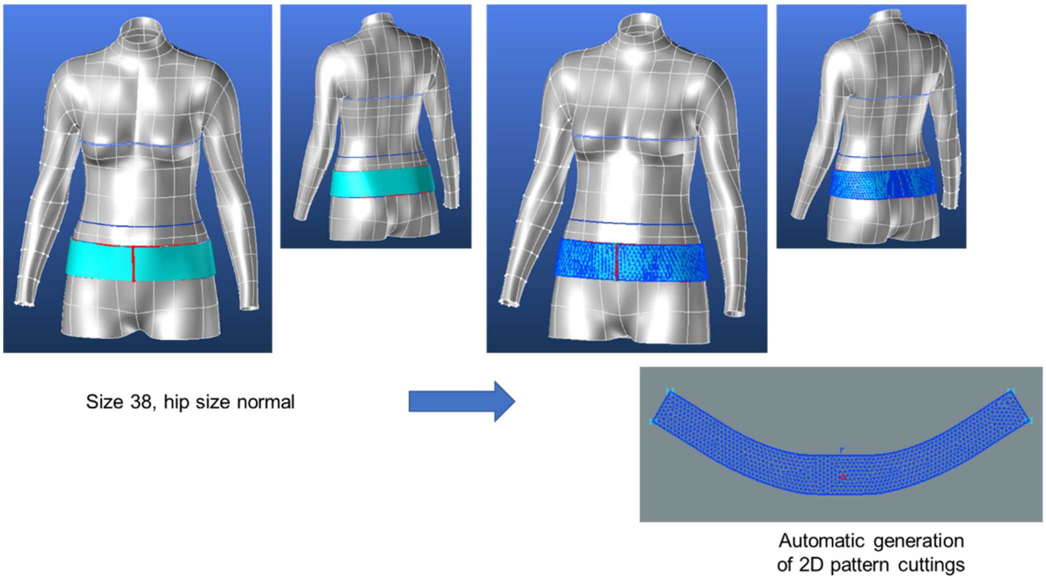

Fig. 2. Generation of flat patterns using an unfolding tool in Lectra Design Concept software

The calculation of the 2D pattern pieces for the required body sizes is done without the usual 2D grading on the basis of the body shape data and corresponds to a morphological grading in 3D. To realise the processing of free-form surfaces (cover of the belt system), the software provides suitable mathematical algorithms. Figure 3 illustrates the morphological grading of the 2D pattern pieces in sizes 38-54, which were automatically generated.

Fig. 3. Comparison of 2D pattern cuttings

2.3. Clustering of the belt pattern outlines by averaged curvature criterion

2.4.1. Curvature estimation

The boundary curves of the belt pattern were determined experimentally and are irregular graphical curves with variable curvature. They differ markedly in the magnitude of curvature (boundary curve bending).

To determine the curvature of the non-relative original curves, they were parameterised: the curve was divided into *n* equal segments and represented by a discrete point series, which were smoothed by the Balanced Discrete Curve (BDC) approximation method [9]. The local curvature is calculated at each point by Discrete Differential Geometry (DDG) methods. The plot of curvature variation along the curve is independent of the degree of curve discretisation. To evaluate the curvature of the curve as a whole, the arithmetic mean curvature (the average curvature) is calculated. This value allows us to compare how much different curves are bent on average, irrespective of their length.

2.4.2. Cluster analysis

To cluster the flat patterns, the authors needed to identify a vector of criteria to determine their similarity. Thus, as a criterion for pattern clustering, it is obvious to choose the curvature value of flat pattern lines. Another clustering criterion is the length of the lines, with an equal interval of 6 cm within a group.

Discretisation and smoothing methods were used to average the lines of one cluster. The upper outline curves of each pattern were converted into discrete series of points, which were combined into a point cloud and approximated by the BDC method to determine the averaged template. The approach has demonstrated its effectiveness in analysing and clustering curves of different shapes and sizes.

This algorithm is implemented quite successfully in Rhino & Grasshopper software. Grasshopper, together with Rhino 3D, is the most well-known visual programming tool for parametric modeling. This software environment allows efficiently and correctly calculating and visualizing complex geometric shapes, which significantly facilitates the process of modeling and analysis in real-world applications.

3. Results

The resulting curves, obtained through surface unfolding, have been saved in the DXF format. DXF (Drawing Exchange Format) is a vector file format that is commonly used for the storage of 2D and 3D drawings in the CAD industry. To facilitate further mathematical processing of the obtained curves, it was necessary to convert the vector curves into coordinate points. To this end, a script was written in Python and executed in order to obtain the requisite data. Following this processing, all data were available in the XLSX format as a coordinate point list.

The subsequent objective was to calculate the curvature of the obtained curves, which describes the geometry of the lower hip area in terms of different figure types and sizes. The methodology described below was employed to analyse the curvature and calculate the average value (Fig. 4). The curvature was characterised both graphically, as the distribution of this parameter across the discrete points of the curves, and numerically, as the mean value for each figure type. The highest curvatures are observed in the vertebral region for all curves. The curvature decreases in the lateral area and then begins to grow again in the abdomen.

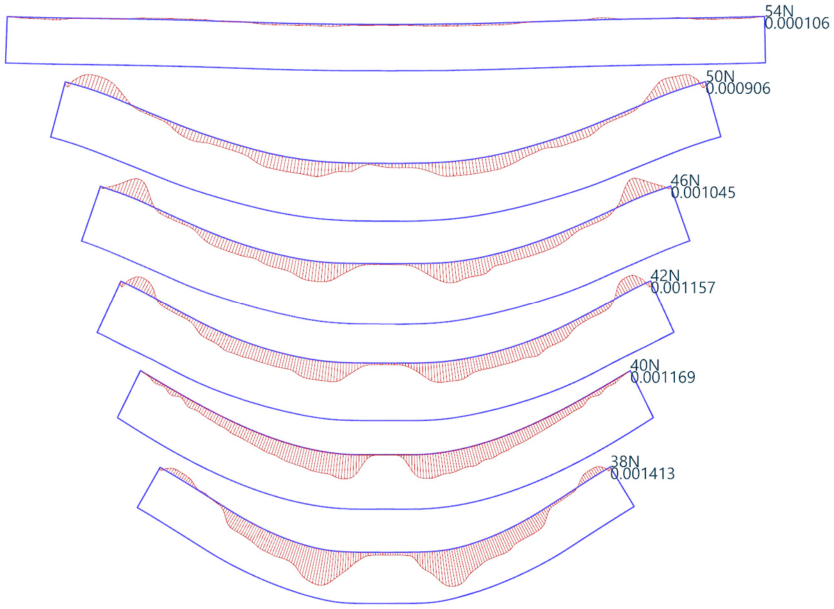

Fig. 4. Comparative analysis of the curvature of belt pattern outlines.

A regression analysis was conducted on the resulting data obtain the sizes that had been omitted during the flattering pattern process. The process can be described as a polynomial equation with a high level of correlation, exceeding 0.99. As can be observed on the graph (Figure 5), there is an inverse relationship between curvature and length. The trend is observed to shift from smaller to larger sizes. The smaller sizes exhibit a slight increase in length, accompanied by a corresponding decrease in curvature. Conversely, the larger sizes display a decrease in length, accompanied by an increase in curvature.

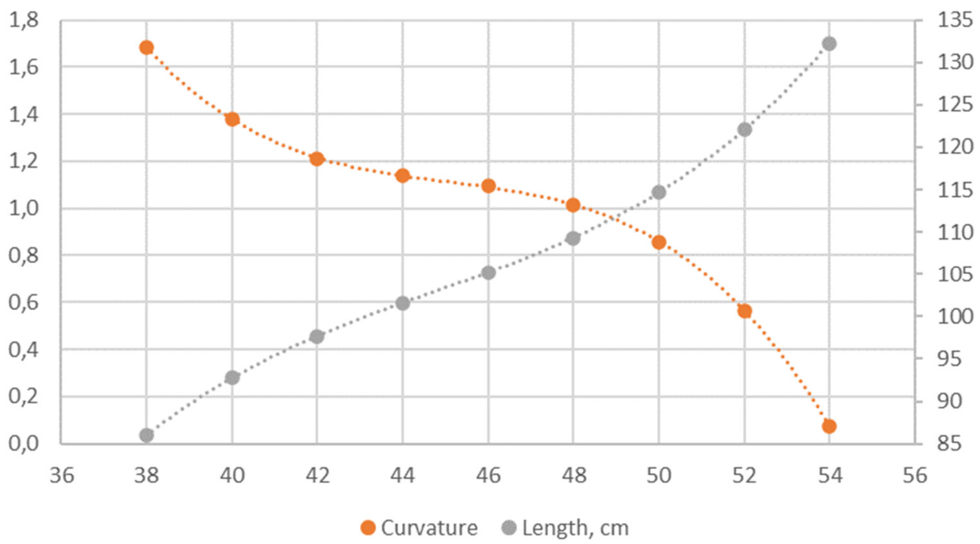

Fig. 5. Relationship between curvature and length of the belt pattern upper lines for a selected size range.

The subsequent stage involved the application of a clustering technique to the systemised values for length and curvature obtained for a range of sizes and figure types. To compare curvature and length, which have different units and numerical scales normalisation by min-max scaling on the range (0,..., 1) was performed. In the graph (Figure 6), each point is a model of a separate template with coordinates as normalised length and curvature parameters. The analysis showed the prioritisation of the length criterion for clustering.

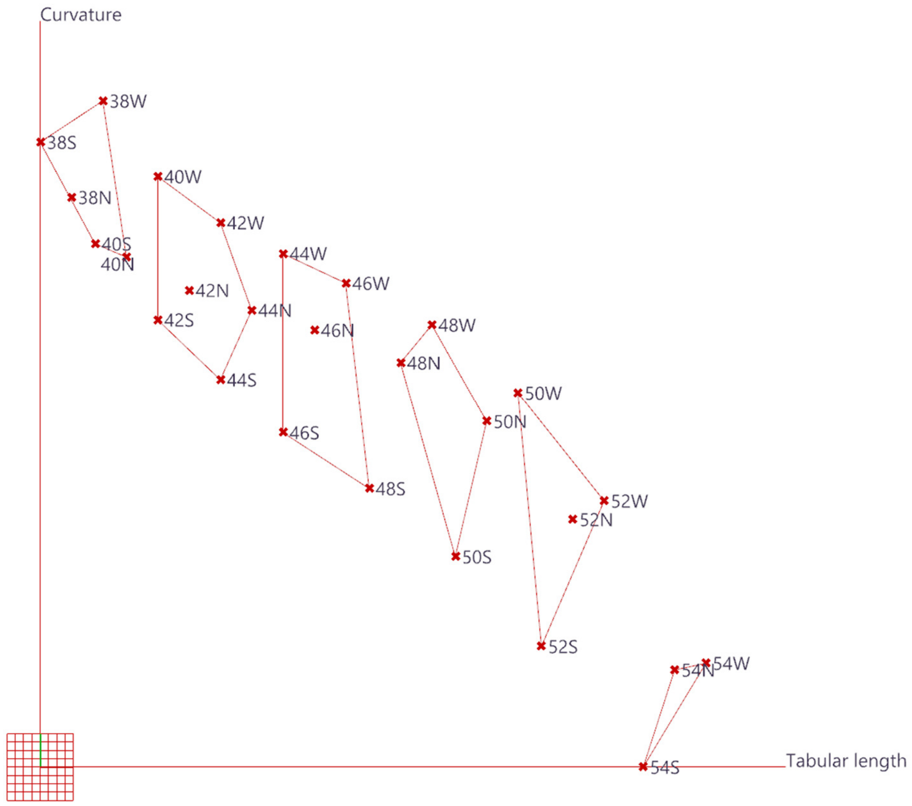

Fig. 6. Cluster analysis based on normalised length and curvature values.

The cluster analysis allowed us to identify six clusters based on the similarity of the compared parameters within the given ranges. The number of clusters can be varied - this is a controllable parameter of the method. Each cluster adequately represents the group of sizes. The discrepancy in length does not exceed 6 cm, while the difference in curvature remains within the limits of the percentage. This distribution option is optimal for ensuring comprehensive coverage of all types of body shapes within the specified size interval, thereby guaranteeing that the developed pattern samples align closely with the geometry of the lower support surface of the body of the shape.

The objective of the subsequent research phase was to generate averaged curves that would accurately depict the length and curvature of the surface under investigation within the specified interval. To achieve this objective, a set of curves belonging to the same cluster was represented as points using the aforementioned method. Subsequently, a smoothing approximation utilising the method of normals was applied to the resulting point set. The outcome is illustrated in the accompanying Figure 7.

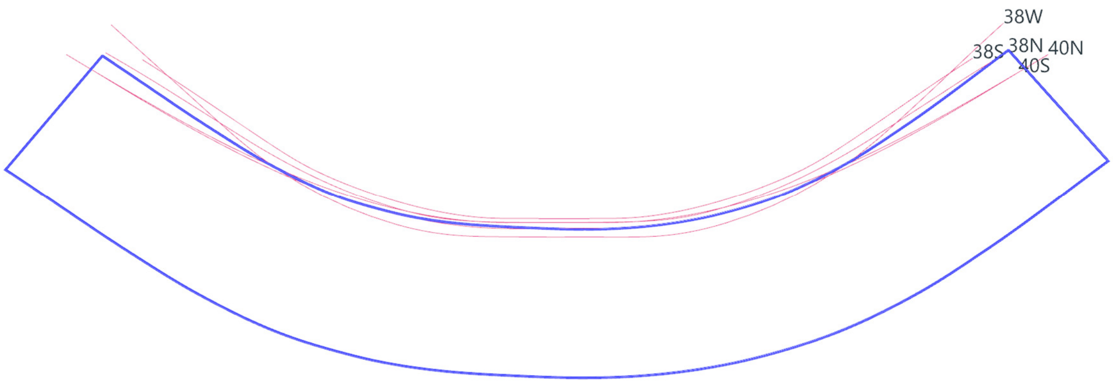

Fig. 7. Modelling patterns based on the lines of particular clusters.

4. Conclusions

The rapid advancement of scanning technologies has significantly enhanced the ability to design products that closely align with the contours of the human body. This research has developed a methodology that bridges the gap between the need for mass production and the necessity for a precise fit, with a particular focus on function-specific harness systems incorporating tool-bearing or assembly belts. The utilisation of parametric human models based on standard sizes and hip width variants enabled the accurate modelling and design of belt systems that conformed to the distinctive geometry of the lower body surface, particularly between the waist and hip.

The automated process of unfolding three-dimensional designs into two-dimensional patterns, followed by the verification of anthropometric fit through simulations, ensures that the resulting products maintain a high level of functionality, comfort, and manufacturability. This methodology permits the efficient production of load-bearing products, including backpacks, tactical harnesses, and baby carriers, which necessitate a substantial contact area to optimally distribute weight across the body. Given the practical nature of the findings, they can be readily applied in the apparel industry.

Further research should investigate the potential for extending this approach to a broader range of products, including the possibility of dynamic fit for garments that adapt to body movement. Furthermore, the integration of more detailed considerations regarding material behavior into the design process would serve to enhance the adaptability of mass-produced functional items.

Acknowledgment

The authors express their gratitude to the Philipp Schwartz Initiative of Alexander von Humboldt Stiftung for funding this research as a part of the fellowship program of Nataliya Sadretdinova.

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