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Shape Adaptive Cut Lines

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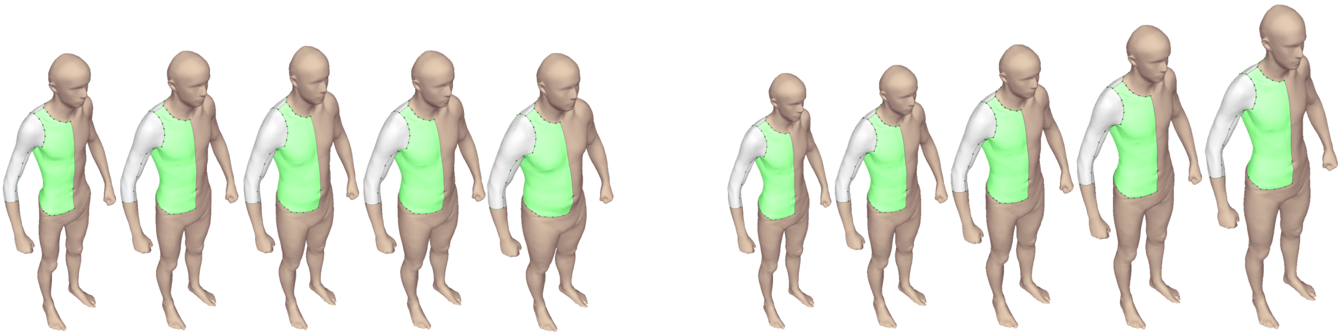

Figure 1: *A template garment is attached to a statistical shape model. Deforming the Avatar along the first two principal directions leads to adapted cloth patches.*

Abstract

We present a novel method to express base layer and compression garments directly coupled to a human body geometry. Our system enables the transfer of a previously defined patch configuration from a virtual template avatar to arbitrary input bodies. A complete pipeline for the virtual development of second skin garments is presented. The system's strength is the transparent usage for two important scenarios in the apparel industry. On the one hand grading for a population is presented using body shape statistics without using any measurements and on the other hand an approach for custom garment creation in a made-to-shape fashion is proposed.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Line and curve generation—I.3.5 [Computer Graphics]: Curve, surface, solid, and object representation—

1. Introduction

With the increasing availability of CAD software for apparel development and new fabrication methods, virtual prototyping and design becomes increasingly important. Reduced time frames and costs are the result of a virtual work environment. A variety of process steps in apparel design and development are well covered by existing virtualization solutions. There exist technologies for body shape acquisition, analysis, the virtual assembly of color ways and even the construction of garments. In contrast, the process of pattern grading is still manual work that requires lots of expertise and empirical knowledge. Grading represents the process of adapting a garment to various body sizes. This involves the statistical analysis of a target population and the development of measurement transition tables. To tackle the complex process of describing a human body's shape, its definition usually is reduced to a set of 1D measurements. This can be seen as a heavy under sampling, leading to a significant loss of shape information. In addition, rules regarding ratios have to be taken into account. Developing a pattern based on measurements will always imply interpolation and may lead to approximation errors and – as a consequence – garments that do not fit. Using the surface as body shape description leads to an unified representation without the mentioned loss of information. Although, the acquisition of the body surface is not as accessible as taking measurements with a tape, a shape based garment grading is shown to be superior to a measurement based approach. To integrate the shape based paradigm back into the traditional work flow,

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measurements can be extracted from virtual bodies.

Body scanning allows us to represent a human body not only by a set of measurements but by an arbitrarily close discretization of its surface. Further steps in the development process for cloth can benefit from this high amount of shape information. Since a garment's pieces are cut out of fabric they naturally exist in a flat domain. Therefore, pattern development by today is a 2D process.

Considering a worn garment as a joined set of sewn cut pieces, a bijective mapping exists between the flat cut fabric and the spatially folded garment. With this, we are able to define the pattern development process as a problem coupled to the body surface. Contours are defined relative to the avatar and follow its deformation. Subsequently, patches are cut out along these contours and flattened to pattern space, using a distortion minimizing parameterization with free boundaries. This way, we introduce grading of a fabric piece as the process of deforming the host geometry. To bring compression into the garment a scaling is applied on the flat pattern pieces in the fabric's warp and weft direction. In summary, we developed a complete pipeline for base layer garment development including the possibility of a fully automatic body shape based grading. The work's contributions are:

- A pure shape based spatial gradation without the need of body measurement.
- made-to-scan: Shape based enhancement of made-to-measure base layer garments.
- Body coupled cut lines that lead to morphable pattern.
- Evaluation of the pipeline by fabricated prototypes.

2. Related Work

In apparel industry, virtualization is a fast growing field since development, prototyping, testing and fitting benefit from its advantages. A substantial overview of geometry modeling and virtual apparel design is provided by Thalmann et al. [MT10] and Liu et al. [LZY10]. Wang et al. [WWY05] presented an automatic made-to-measure approach for loose fitted non-compressive garments based on a non-manifold encoding of the garment on the body shape. They use freeform surfaces to encode the garments with the body shapes and perform morphing. In their spirit, we use a more direct coupling of the base layer with the body surface and show the results with real fabricated prototypes. Bouret et al. [BSBC12] presented work to transfer a virtual 3D garment between different shaped characters. They use offset vectors to couple the garment and the body geometry and exhibit the fact of a cross parameterization between different shapes. Extracting 2D sewing patterns to automatically create 3D cloth assets is presented by Berthouzoz et al. [BGK*13]. Methods for sketch based virtual cloth design have been presented by Yasseen et al. [YNB*13], Umetani et al. [UKIG11] and earlier by Turquin et al. [TWB*07]. Decaudin et al. [DJW*06] have shown a method of extracting 3D cloth models out of seam lines applied directly to the host geometry. Their work also provides a technique of segmenting and flattening sewing pattern out of the models. A comprehensive technique to design 3D garment models via contour curves is shown by Wang et al. [WLL*09]. In virtual fitting Meng et al. [MMJ12] presented a method of design garment pattern via 3D editing methods. Xu et al. [XUC*14] presented a work of real-time virtual cloth synthesis based on a set of learned cloth deformations. 3D body scanning systems provide dense point sets representing human geometry. Allen et al [ACP03] presented a method to transfer them into watertight mesh representations tackling the hole closure problem as well as holding correspondences between different shapes. A lattice based deformation method is introduced by Zollhöfer et al. [ZSGS12]. This system in combination with a pose normalization is used by Colaianni et al. [CZS*14] for non-rigid registration of template meshes with scan data. In the field of capturing virtual geometries from prototyped garments via color pattern, we refer to Scholz et al. [SSK*05a]. Based on the morphable model of Blanz et al. [BV99], Allen et al. [ACP03] provided a method for representing human body geometry within a statistical model. Applied dimensionality reduction methods as PCA gives the possibility of shape synthesis in a statistically meaningful way. The problem of unwrapping curved surfaces into a flat domain is an extensively discussed topic in many areas. In computer graphics the parameterization problem, for example, is used to texture objects. A comprehensive overview to the parameterization problem is given by Floater and Hormann [FH05]. Free-boundary parameterizations that minimize the distortion on surface are introduced by Liu et al. [LZX*08] based on the work of Sorkine et. al [SA07]. To make compressive garments, a shrinkage is performed on the cut piece. Substantial work is presented by Sybille Krzywinski [Krz05]. CAESAR, a large database of human body scans, is provided by [Pol02] and automatic landmark-extraction is described in [LW09].

3. System Overview

Our system – as shown in Figure 2 – is able to generate a garment directly for a given body shape. It consists of the following parts:

- The **template** is a polygonal, watertight mesh, semantically representing a human body. **Cut lines** are paths defined relative to the template. The content at this stage is prepared by an apparel designer and can be modified independently from the geometries used afterwards.
- The deformation stage is split into multiple possible inputs. Depending on the scenario of use either a **statistical** shape model or a single **registered scan** can be used to synthesize shapes.
- In **decoding**, the set of cut lines stored for the template are extracted for the target geometry. The closed garment patches are cut out of the target bodies surface.
- Subsequently, the patches are **flattened** using a distortion minimizing parameterization and scaled for compression.

The strength of the presented system is its versatility depending on the used scenario. On the one hand, the contours can be morphed to match synthesized instances out of a body shape statistic. On the other hand the same method can be used to generate base layer garments for distinct persons via their body scan.

3.1. Shape Based Grading

One capability of contours defined relatively with respect to the body is an inherent grading system. Instead of defining transitions

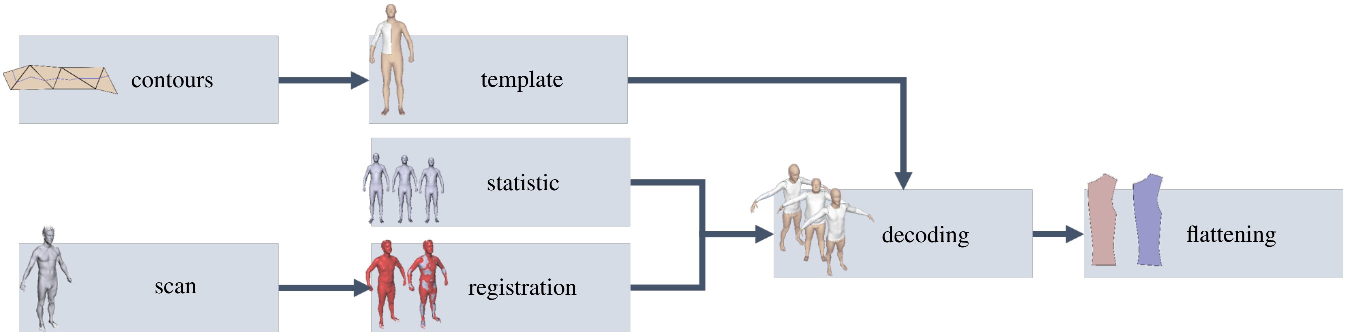

Figure 2: *The presented system holds a template cut line configuration on a default avatar. Either a statistical shape model or a registered scan – both sharing the topology with the template – can drive the surface contour deformation. The decoded contours are used to cut patches out of the target. Via flattening the patterns are generated.*

between different sizes depending on measurement charts our system is used to match avatars representing different sizes by solely using their geometry. As a result, the size range for a population is generated by sampling the most significant principal components of a statistical shape model (see Figure 1). Using k-means clustering for the shape based extraction of well representing shapes in brassiere construction is presented by Colaianni et al. [CSP*15]. We show the flexibility in defining a population coverage in Section 7.1.

3.2. Made-To-Scan

Made-to-measure is a garment development method that focuses on the pattern assembly based on individual body measurements, carried out by a pattern maker. Without modification, the presented system is used to cover another scenario similar to that technique, we refer to as made-to-scan. A garment is constructed to fit an individual person in a tailor-made fashion. In contrast to made-to-measure, we do not use any body measurements but directly morph the contours to fit body scans. Figure 3 demonstrates the cut lines adapting to three different shapes of scanned persons, Section 7.2 presents sewn prototypes for this bodies with compression analysis.

4. Surface Linked Contours

The presented method focuses on zero distance and compression garments, also known as base layer. With this prerequisite, the garment's patches can be seen as a subset of the body's surface (see Figure 4). To define patches, a designer draws contours directly on the avatar's surface. In order to get the contours deformed to arbitrary body shapes, an encoding of the paths along the polygon mesh's surface is crucial. Contours are piecewise linear segments between surface points on a polygonal mesh(see Figure 5 (left)). Such a surface point is defined as a convex combination of the surrounding vertices. Given a point $\mathcal{P}_i$ within a triangle $\mathrm{T}_i = \{\mathbf{v_0}, \mathbf{v_1}, \mathbf{v_2}\}$ encoded with the corner weights $\mathrm{w}_i = \{w_0, w_1, w_2\}$ the position $\mathbf{p}(\mathcal{P}_i)$ is directly inferred by $\sum_0^2 w_i \cdot \mathbf{v_i}$. This way a surface point is moving relative to the triangle (see Figure 5 (right)). As a consequence all contours – and therefore the patches – follow the deformation of the embedding mesh. To enable an accurate morphing between different meshes they need to share semantic per-vertex correspondences. Extracting closed patches from the avatar's surface, simple triangle cuts are applied to split the host geometry along contour paths. As these cuts may lead to an invalid mesh configuration, triangulation of resulting non triangular polygons is performed. Because of a possibly poor triangulation of the resulting patch, re-meshing becomes necessary (see [AVDI03]). Some cut examples of surface patches are shown in Figure 4.

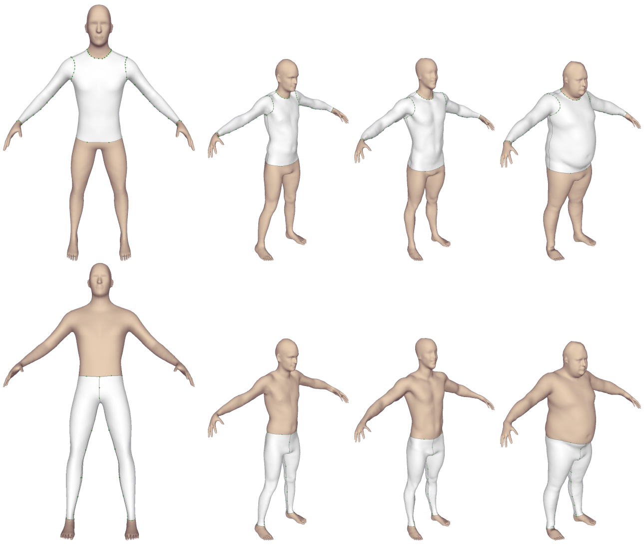

Figure 3: *Two sets of contours originally encoded for a template body shape (left) are morphed to fit different shapes (right). The top row shows a compression long sleeve the bottom row a tight pant.*

5. Body Deformation Models

The presented method uses polygonal meshes as a virtual representation of human bodies. The deformation of the attached base layer contours is driven by the body shape deformation. Amongst other

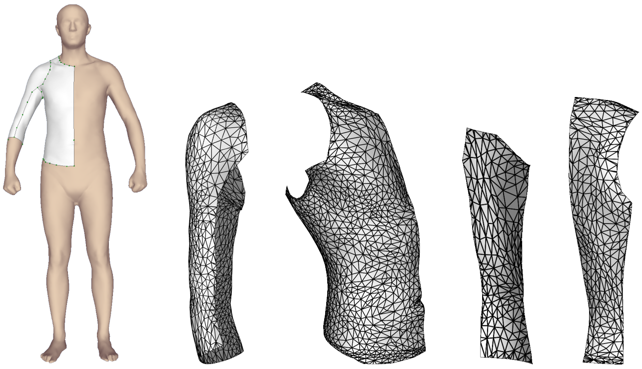

Figure 4: *A subset of the avatar's surface is a patch bounded by cut lines. The cut patches are the prior geometry for the flat patterns.*

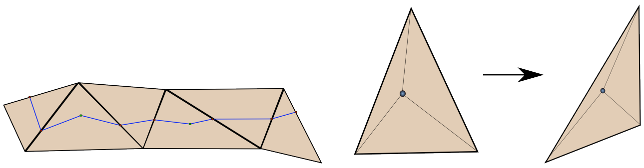

Figure 5: *A surface path is the piecewise linear connection of surface points (left). These are relatively stored regarding the containing polygon. Thus, they follow deformations of the host triangle.*

possibilities, we discuss two different ways for mesh deformation relevant to our work. Regardless of the used deformation method it is necessary to maintain the semantic meaning for each surface position. The quality of garment adaption is tightly coupled with the accuracy of these correspondences.

5.1. Statistical Body Shape Models

When the system is used for the grading of a population a morphable model is used as described in [BV99, ACP03]. In principle, these methods start from a certain amount of registered body scans. Cross-correspondences between used instances are maintained by using topologically equivalent meshes for building the shape statistic. To minimize the correlation of shape and posture, a pose-normalizing step (see [CZS*14]) is applied on the input data. Using a shape statistic for performing the presented shape based grading technique exhibits two advantages over a measurement based approach. On the one hand the shape information is fully maintained by using the vertex positions instead of measurements and on the other hand a statistical shape model represents a given population spread well. The desired statistical properties, as for example mean shape and variance, are preserved.

5.2. Registration of Scanned Data

Instead of using body shape statistics, the contour can also be used to fit an individual scan. The template avatar is registered to the input scan data as described in [ACP03]. This ensures the result to be semantically consistent with respect to the contours. We use a lattices based deformation method as described in [ZSGS12, CZS*14]. The core idea of this algorithm is to embed the template in a volumetric proxy grid and perform ARAP-deformation on that lattice. Then, the meshes are decoded using the deformed grid. Figure 9 depicts some results of the registration. The presented method uses auto-generated landmarks provided by the scan system as fix target positions for constraining some vertices. With this, a fully automatic registration of scan data is possible and the system is able to generate fitted close to body cut lines, immediately.

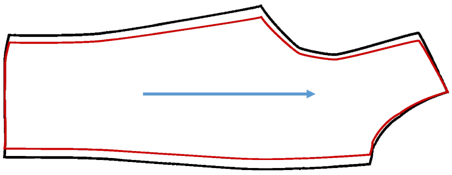

Figure 6: *A parameterized (black contour) and subsequently flattened (red contour) cut piece. The blue arrow illustrates warp-direction.*

6. ARAP-Parameterization

For flattening patches we use a parameterization based on the work of Liu et al. [LZX*08] with a subsequent scaling to make the garments compressive. They presented a parameterization that solves for the best transformations of the mesh's triangles in order to minimize the per surface distortion. The method solves the ARAP Energy via iteratively stepping between a local phase to find the best per triangle rotations and a global phase to solve for the best vertex positions.

6.1. Pattern Shrinkage for Compressive Garments

When shrinking pattern to develop compression garments the desired force transferred to the body has to be taken into account. It is desirable to produce garments with controlled compression in order to support or counteract body motion. Usually, close to body worn apparel is scaled to achieve different strengths of compression behavior (see [Krz05]). The shrinkage is applied to each vertex v_i of the flat pattern:

$$v_{i,scaled} = \begin{pmatrix} \frac{1}{1+\frac{\varepsilon_u}{N}} & 0 \\ 0 & \frac{1}{1+\varepsilon_v} \end{pmatrix} \cdot v_i$$

The pattern's warp is assumed to be in x- and weft in y-direction. ε_u and ε_v are the prolongations of the *stitch wales* in respective directions – a material parameter of the fabric. Different compression amounts can be set by $N = \{1,2,3,4\}$. The warp direction as well as a scaled pattern is depicted in Figure 6. To get a properly aligned placement of the pattern on the fabric, we have to automatically extract the main warp-direction. In order to do this, we project the avatars *up*-direction onto each vertex (see Figure 7, left). Subsequently, we transform these vectors per vertex in the flat parameter-domain. The representing warp-direction for the pattern is the averaged direction of all vertices (compare Figure 7, right).

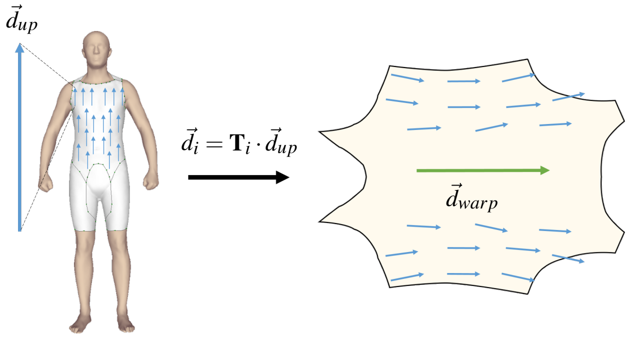

Figure 7: *The avatar's aligned up-vector* $\vec{d}_{up}$ *is applied to each vertex of the 3D garment (left), mapped to the flat pattern and averaged. The resulting average (green vector, right) is aligned with the fabric's warp.*

7. Results

7.1. Pattern Development for a Population

For grading a basic template to fit a population, we synthesized body shapes using a shape statistic (compare [BV99, ACP03]) built from CAESAR scans (see [Pol02]). We used a one sided contour configuration as this is common for symmetric garment development in industry. The template configuration is shown in Figure 8. Since this implicit way of grading is not dependent on a specific measurement system, one is able to freely grade through the space of body shapes. In the absence of a direct mapping between body measurements and the coefficients of a morphable model we decided to synthesize body shape avatars along the first two principal components of the shape statistic. We show 10 synthesized body shapes along the two most significant k-means clustered principal directions in Figure 1. The corresponding patterns are shown in Figure 8. Note, that the first direction of the statistical model has more variation in circumference than in size. Body height is distributed along the second principal component. This result emphasizes the system's capability of grading according to geometry instead of using measurements.

7.2. Made-To-Scan Prototyping

Our system has the ability of adapting garment contours to arbitrary human shapes. This method now is used to develop custom made garments based on a body scan. We call this approach made-to-scan. We compare our method to the gold standard of made-to-measure garments which is based on 1D measurements. For testing we used body scans of three individual persons with a high variation in their body shape (see Figure 9). A designed set of contours for a compression long sleeve and a tight pant as well as its decoding for the three different test shapes are shown in Figure 3. The sewn prototypes are shown in Figure 9. Producing functional garments, compression is a relevant issue to support or counteract the motion of body movement. For best wearing comfort a homogeneous distribution of compression is desired. We compared our custom made shape based garments with a set of cloths prototyped by a pattern maker using the made-to-measure method. The stretch behavior (and thus the compression distribution) of the worn garments is measured by analyzing the per surface deformation of the prototypes. For the acquisition of the stretch, the prototypes are made of fabric with a pre-applied color pattern. Using RGB images the deformation can be recovered using a system related to the work of Scholz et al. [SSK*05a]). The resulting deformation distribution over the surface is shown in Figure 10. Since made-to-scan carves the cloth patches out of the surface shape, the stretch behaves more uniformly even in more complex shaped regions. In addition, this method does not involve pattern construction knowledge in the stage of shape adaption. It entirely relies on the geometry information provided by the host shape.

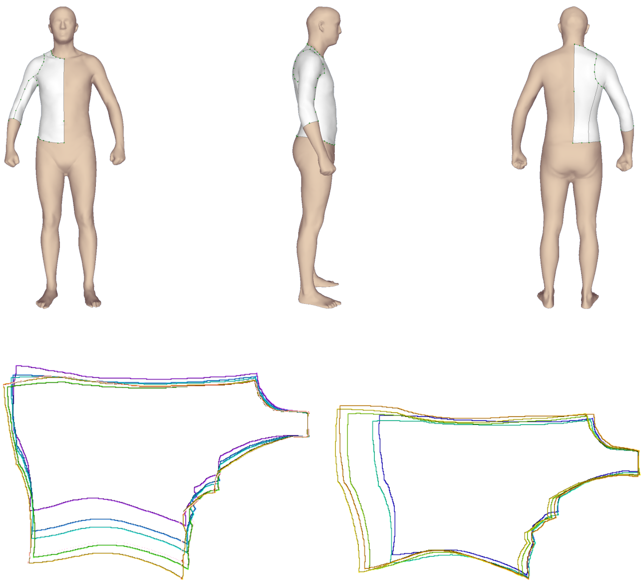

Figure 8: *Top row: The test shirt contour configuration used for the shape based grading test. Bottom row: Two sets of graded cut pieces along the first principal components of a body shape statistic.*

8. Limitations

There are some limitations to our method we want to discuss. First, the presented system is only suitable for base layer garments. Since the patches are defined as subsets of the body surface a model for loose fitted garment is missing in this work. Another limitation is the flattened patches not being immediately usable as a pattern. They can be seen more like a *pattern-prior* containing all the necessary shape information. To get a production cut piece, post processing such as applying inlays and seam allowance is needed (see Figure 11). While for the presented tests, these steps are done by a pattern maker, these steps could easily be automated. Furthermore, there is no global coupling between the cut patches within the parameterization stage. Thus, connected seams theoretically are not constrained to be of equal length. Especially in spherically shaped regions (e.g. the shoulder) this fact leads to a need for manual post processing. Additionally, the indirect contour deformation method directly depends on the semantic quality of the host mesh. An auto-

Figure 9: *Left: Registration Results for three test persons. The template (gray) is deformed to best match with the scan (red). Right: The made-to-scan developed prototype suits made of a fabric with color pattern.*

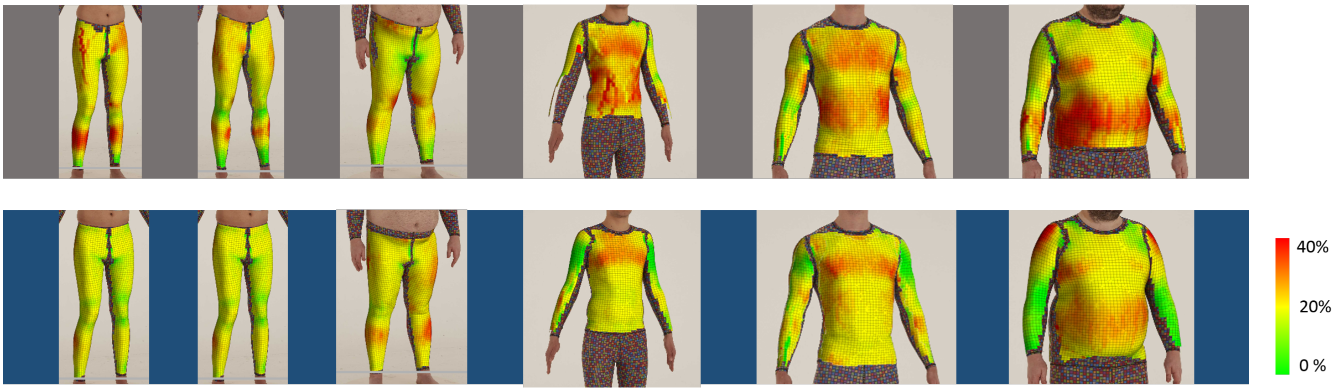

Figure 10: *Sewn prototypes with visualized compression over surface for the tight pant and the long sleeve. The color indicates the percentage of deformation in warp direction (see scale right). The top row shows the manual made-to-measure, the bottom row our presented made-to-scan results.*

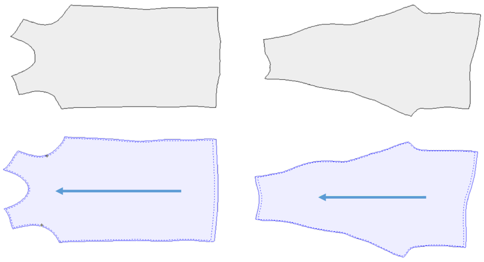

Figure 11: *The presented system produces pattern priors (top row) have to be manually post processed in order to be producible (bottom row).*

matic registration of scanned data can cause tangential drift of the vertices and at worst they lose their semantic meaning.

9. Conclusion and Future Work

We presented a method for creating base layer garments directly on virtual human avatars. A garment is designed on a default template avatar and then adapted to a scan or shape statistic. The possibility of defining cloth contours coupled to the body shape enables a direct grading, that follows different body shapes very accurately. Transferring this work to a more general description of body encoded garments is an interesting field for further research. We also have shown the method to be robust for made-to-scan garment. Instead of using body measurements for pattern development the method works solely on the shape. Using principal component analysis on body shape statistics is usable in apparel industry to understand main variations of the body shapes. In connection with the presented work a prototyping of garments for a whole population is possible and leads to a strongly reduced effort in physical prototyping size ranges. The resulting graded garments can compete with or even outperform those made by a professional, while only basic pattern knowledge is required.

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