3D Custom Fit Garment Design with Body Movement

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Fig. 1. Our method supports the creation of custom-fit garments that fit comfortably in a range of different poses. Our input consists of several scanned and registered 3D poses of the intended wearer that the garment needs to accommodate (a). We provide six different tools to design and adjust the initial garment shape for one of the poses, designated as the initial rest-shape (b). We then let the avatar move through the different poses by interpolating the pose meshes and utilizing a cloth simulation. Throughout, we adjust the rest shape of the garment to achieve the final garment shape (c), such that it accommodates all the different poses (e). We use existing surface parameterization methods to create a sewing pattern of the shape (d). We sew a physical garment and verify it on the scanned person (f). Our method is able to create garments for people who fall far outside the range of standard sizes, like this model, whose height is 125 cm. Please refer to the accompanying video for a more detailed view of the dress.

The standardized sizes used in the garment industry do not cover the range of individual differences in body shape for most people, leading to ill-fitting clothes, high return rates and overproduction. Recent research efforts in both industry and academia therefore focus on on-demand fabrication of individually fitting garments. We propose an interactive design tool for creating custom-fit garments based on 3D body scans of the intended wearer. Our method explicitly incorporates transitions between various body poses to ensure a better fit and freedom of movement. The core of our method focuses on tools to create a 3D garment shape directly on an avatar without an underlying sewing pattern, and on the adjustment of that garment’s rest shape while interpolating and moving through the different input poses. We alternate between cloth simulation steps and rest shape adjustment steps based on stretch to achieve the final shape of the garment. At any step in the real-time process, we allow for interactive changes to the garment. Once the garment shape is finalized for production, established techniques can be used to parameterize it into a 2D sewing pattern or transform it into a knitting pattern.

CCS Concepts: • Computing methodologies → Computer graphics; Shape modeling; Mesh geometry models; Digital Garments.

Additional Key Words and Phrases: computational fabrication, garment modeling, cloth simulation

1 INTRODUCTION

The garment industry is a trillion-dollar, global industry that uses a large amount of natural and human resources [Bick et al. 2018]. According to recent research, of all annually manufactured garments, 25% are never sold, and another 25% are sold but almost never worn [Morlet et al. 2017], meaning that nearly half of the produced items are imminently destined for landfill or incineration. One reason is that for many people it can be challenging to find fitting clothes, as standardized sizes often cannot account for individual differences, such as longer or shorter arms, asymmetries, body dimensions that...
Fig. 2. We compare a standard shirt of size 43, modern fit (top row) with our custom-fit shirt (bottom row). Our shirt fits more tightly to the body (left), while allowing more comfort in a range of motions (middle and right). The standard shirt stretches and tightens uncomfortably when the arms are outstretched to the front (middle). Lifting the arms leads to pulled down sleeves and uncomfortable stretch along the arms of the standard shirt (right). See Fig. 11 for more details of our custom-fit shirt.

fall outside the commercially available range or even missing extremities. Standard sizes available in stores vary over the globe; in Germany, 70% of women do not fit the commonly available standard sizes [SizeGermany 2020]. Moreover, people who share the same standard measurements might still vary drastically in their body shape. All these issues lead to high return rates of purchased garments. In recent years, on-demand, individualized fashion has become a focus in research and industry as a response to these problems. Still, the garment industry so far remains largely unchanged and depends on strenuous manual labor and mass-produced ready-to-wear garments. Fitting garments individually is currently a manual and expensive process done by professional tailors, who adjust existing sewing patterns to the person’s size and features while leaving the overall pattern design unchanged. This process did not substantially change for centuries. Even modern computer based garment design systems, like CLO 3D [CLO 2020], still rely on traditional 2D sewing patterns as their central design space.

We take a radically different design approach, which is liberated from 2D sewing patterns and focuses on maximum fit and comfort under a range of individual motions for any kind of body shape. Our method creates an optimized shape of the garment, and only in a second step prepares it for production using existing techniques. We create completely new sewing pattern designs via 2D parametrization. Alternatively seamless knitting patterns can be generated based on our designs, sidestepping the use of 2D sewing patterns completely. We purposely step away from traditional sewing pattern designs and symmetry, but nevertheless still allow the traditional positioning of seams if desired.

We work with a variety of poses for each person: we scan each pose using a commercial 3D scanner and use existing methods to register a template body mesh to each scanned pose, such that we obtain pose meshes of matching connectivity. This provides us with higher fidelity to the true shape of the user’s body than simply using a few standard measurements and a pre-set, symmetric avatar, and also helps eliminating measurement errors by the user. For each garment we use a select number of poses that this garment needs to accommodate. We provide a set of intuitive tools to design the garment shape directly in 3D, sidestepping the necessity for creating an underlying sewing pattern. We enable the drawing of garment boundaries directly on the avatar to create skintight clothing, but also allow for the addition of loose parts. An optional paintbrush tool can be used to add cloth in specified regions, and by defining a minimum distance of the garment to the body, we can explicitly control comfort. The garment is then simulated using existing cloth simulation techniques. We maintain a rest shape, which is the garment without any forces applied and a simulation shape which represents the current simulation mesh undergoing stretching, bending and shearing as it is deformed by the dynamic body mesh. While smoothly transitioning between different poses, we compute a stretch metric of the garment and adjust the garment rest shape whenever the stretch exceeds a threshold. This process is fast and allows real-time interaction to adjust the garment at any point in the process. The rest shape can then be used for production, e.g., by applying existing methods to compute a distortion-minimizing sewing pattern. The resulting garments fit more tightly, while allowing a wider range of motions compared to garments of standard sizes (see Fig. 2).

We make the following contributions:
• The introduction of a toolset to easily create 3D garment shapes on a 3D avatar;
• The incorporation of varying body poses and body movements into the design optimization of custom-fit garments;
• The formulation of an iterative garment adjustment algorithm based on stretch.

Using our software, we create a number of garments for people of widely varying stature and body type and demonstrate professionally manufactured garments based on these designs in Figs. 1, 2, 13-15, and in the accompanying video. We make our source code publicly available to foster further research in this area.

2 RELATED WORK
Computational garment design has become a highly active research field in different scientific areas over the past years. We concentrate
on the most relevant works in relation to our contribution and group them according to their focus on garment design, fit and simulation.

Garment design. Works on garment design focus mainly on providing tools for automatically creating and manipulating the garments and their underlying sewing patterns, such that designers can easily and quickly explore design choices. Nayak and Padhye [2017] broadly survey the use of automation in garment manufacturing, including computer aided design. Early works focus on interactive design and modification pipelines, providing visual real time feedback [Keckeisen et al. 2004; Volino et al. 2005]. Berthouzoz et al. [2013] scan and parse existing, traditionally published patterns and convert them into 3D garment models. Umetani et al. [2011] introduce a system for bidirectional interactive garment design that allows to edit both the 2D pattern and the 3D garment shape, while keeping the correspondence between the two. To facilitate fabrication of computed patterns, Igarashi et al. [2008] automatically generate necessary seam allowance for sewing. Several commercial CAD fashion design softwares are available nowadays, including CLO 3D [2020] and Optitex [2020], which enable the digital design of sewing patterns and their draping, greatly accelerating the iterative design process. However, they still follow the traditional design workflow, which requires a professional garment designer with experience in modifying 2D sewing patterns.

A multitude of sketch based methods [Decaudin et al. 2006; Robinson et al. 2011; Rose et al. 2007; Turquin et al. 2007] create 3D garment shapes from contours, boundary lines and seam lines that are drawn on a digital model. Since garments are sewn from flat sheets of cloth, developable patches are automatically computed for the sewing pattern. Incorporating advancements in machine learning, Wang et al. [2018] use a data-driven approach to estimate garment shapes from a sketch of a desired fold pattern. Instead of creating a new garment, the approach by Li et al. [2018] enriches a garment with folds and pleats guided by sketches. In order to incorporate the traditional workflow of pattern design while keeping the advantages of working digitally, Wibowo et al. [2012] use a physical real-world mannequin as a guide for drawing with a specialized tool in 3D around it.

Up until now, if a garment is meant to be sewn (instead of being used solely on digital avatars), the design of the garment is based on an underlying sewing pattern created by a skilled professional who ensures fit and style. When creating a new custom-fit garment, we take a radically different design approach, only focusing on the 3D shape and fit of a garment first. The resulting shape can be directly knit [Narayanan et al. 2019] or flattened with minimal distortion by existing parametrization methods, such as [Sharp and Crane 2018]. The resulting garments show a novel and intriguing style and differ significantly from traditional sewing patterns. Similarly, Kwok et al. [2016] create styling curves directly on the avatar to create novel sewing pattern designs for sports garments, but in their work, the fit is simply assumed to exist and is not optimized.

Garment fitting. A number of works address custom-fitting garments for different body sizes and shapes. Early research focuses on fitting the 3D shape of a pre-designed template garment to an arbitrarily sized avatar by creating feature correspondences between the avatar and the garment [Cordier et al. 2003; Meng et al. 2012; Wang et al. 2005]. The 2D sewing patterns are only created afterwards through different parametrization methods [Decaudin et al. 2006; Meng et al. 2012; Wang et al. 2005]. The seams that define these pieces are either sketched [Decaudin et al. 2006; Wang et al. 2005] or transferred from the initial input garment [Meng et al. 2012]. Introducing style and fit criteria, like proportion, scale, shape and fit, allows Brouet et al. [2012] to grade existing sewing patterns for largely different body sizes. All these methods suffer from the so called draping effect: Since the 2D sewing patterns are directly parameterized pieces of the 3D garment, the resulting sewn garment deforms further when draped. In contrast, we work with an underlying rest shape of the garment, incorporate movement into the shape adjustment of the garment and allow for an optimized placement of seams.

More recent methods adjust for the draping effect. Bartle et al. [2016] allow users to mix existing garment designs and calculate the sewing pattern inversely from the garment. Wang [2018] solves the garment shape and sewing pattern design as a single nonlinear optimization problem. This method only allows for small changes in avatar size, which are created by applying measurements to deform a base mesh; the method is demonstrated by sewing standard sized garments. In contrast, we incorporate 3D scans of extremely different body shapes to create our garments. Unlike both above methods, our work does not rely on pre-designed sewing patterns and incorporates movement of the body. By working with a 3D rest shape of the garment and optimizing the placement of seams, we also limit the draping effect, allowing us to to incorporate large deformations and asymmetries for custom-made apparel.

The work by Montes et al. [2020] explores the automatic generation of new sewing patterns. They embed the cloth as a two-dimensional elastic membrane in the surface of an elastic body mesh and strongly adjust an initial 2D pattern to create skintight clothing. Their method allows to optimize the layout for multiple poses simultaneously. We also create novel sewing patterns for multiple poses, but in contrast, we do not rely on an initial 2D pattern, and our garment does not need to be skintight and allows wrinkles.

Notably few previous works demonstrate fit with actual sewn garments, and when they do, it is mostly on dolls [Bartle et al. 2016; Brouet et al. 2012; Decaudin et al. 2006]; with the exception of Wang [2018] which demonstrates the fit of the garments on real humans, as we do.

Cloth simulation. The simulation of cloth has been of interest for decades with different foci, approaches and models, depending on whether an application requires speed or physical accuracy and the type of cloth (knit or woven). Cloth elasticity can be simulated based on fast and simple spring models [Choi and Ko 2005; Liu et al. 2013], on continuum models [Baraff and Witkin 1998; Narain et al. 2012], which can work well for woven cloth, or the individual yarns [Cirio et al. 2014; Kaldor et al. 2010], which is very useful in modeling intricate knit patterns or a snag of a single thread. Research has also covered aspects such as collision handling [Bridson et al. 2005; Tang et al. 2018], measurement of cloth elasticity [Miguel et al. 2012; Wang et al. 2011], inextensibility [Goldenthal et al. 2007] or plastic deformations [Jung et al. 2016]. Though our framework is relatively independent of the particular choice of the simulation method, we
do substantially rely on cloth simulation and base our method on
the model by Baraff and Witkin [1998]. The different components
of the energy, such as stretch, bend or shear, can be individually
adjusted [Bergou et al. 2006; Tamstorf and Grinspun 2013].

**Human body modeling.** Our method is targeted at creating gar-
ments for real people. To capture details of individual body shapes,
we therefore rely on the large body of research on object scanning
and body shape modeling, as well as commercially available 3D
scanners. Several methods for fitting a parameterized, articulated
human body model to 3D scans exist, such as the multi-person linear
model SMPL, based on skinning and blend shapes and learned from
thousands of 3D body scans [Loper et al. 2015], the more recent
STAR model [Osman et al. 2020], as well as dynamic models like
Dyna [Pons-Moll et al. 2015]. The FAUST dataset [Bogo et al. 2014]
allows to evaluate and compare body models, and we use several
avatars of this dataset to demonstrate our method. Our framework
is independent of the chosen scanning and registration technique,
which can be replaced once even more accurate future methods
become available.

## 3 METHOD

We start by describing the process to capture and register the 3D
body poses, as well as the interpolation of scanned poses to achieve
smooth motions, using existing techniques (Sec. 3.1). In order to
create a large variety of garments directly on the 3D avatar without
requiring underlying sewing patterns, we introduce six interactive
design tools (Sec. 3.2). Our system adjusts the initial garment shape
by moving through all poses, utilizing a cloth simulation (Sec. 3.3)
and iteratively adjusting the garment shape (Sec. 3.4). The final
shape can then be fabricated (Sec. 3.5).

### 3.1 Body pose acquisition and interpolation

**Acquisition.** In order to incorporate the movement of the human
body in the garment optimization, we capture different static poses of
the individual. The amount and nature of these poses depends
on the desired garment. A comfortably fitting garment designed for
sports requires a wider range of poses than a tight fitting cocktail
dress. A long-sleeved shirt might need two poses to capture bent
and outstretched elbows, as opposed to a short sleeved garment.
The specific technique used to acquire the body poses can be chosen
freely, as long as all poses are represented as meshes with the same
number of vertices and connectivity in full correspondence across
the different poses. We use a Structure Sensor [Occipital 2020] to
scan each pose. The resulting mesh can include background objects,
which we remove, as well as holes and artifacts. Two cleaned up
meshes are shown in Fig. 3 (a). In order to create evenly meshed
poses in full correspondence, we use Meshcapade [Meshcapade 2020]
which employs the SMPL model [Loper et al. 2015] (Fig. 3 (b)). These
technologies can be easily substituted by future developments.

**Interpolation.** During the later garment simulation, we want to
smoothly transition between the captured poses in order to opti-
mize the garment for a range of motions. Given the captured pose
meshes with corresponding vertices and faces, we can readily in-
terpolate these poses. Even though Meshcapade provides skeletons

with each registered pose, we do not use those for interpolation,
for two reasons: (i) We want our algorithm to be independent of
the registration technique and work for methods that do not supply
a skeleton, and (ii) we wish to be able to incorporate changes in
the body shape that are not necessarily captured by skeletal mesh
deformations (skinning), such as movement of fat and tissues, or
volumetric changes for the same pose (e.g., growing belly in preg-
nancy). Therefore, we directly interpolate the pose meshes using a
nonlinear morphing technique akin to deformation transfer [Sum-
ner and Popović 2004] and Poisson shape interpolation [Xu et al.
2006]. In order to get a unique solution, we need to constrain the
position of a single vertex. We choose to constrain the vertex that
moves least between both poses to a linearly interpolated position.
We evenly sample between both poses with a predefined number of
60 interpolation steps (see Fig. 3 (c)), though the number can be
chosen higher or lower, depending on how much the scanned poses
differ.

### 3.2 Digital garment creation

Starting with any of the captured poses, we use it to design the
garment directly in 3D. We propose a set of simple yet powerful
tools that allow to explore the complex space of garment designs:

1. **Boundary tool** to draw garment boundaries on the avatar.
2. **Extension tool** for loose fitting parts.
3. **Paint tool** to add cloth in specific areas.
4. **Pinning tool** to set a minimum distance to the body.
5. **Pinning tool** for garment vertices.
6. **Seam tool** to predefine garment seams.

**Boundary tool.** We allow the user to draw closed loop boundaries
directly on the avatar by consecutively clicking points on the mesh,
which we connect by shortest edge paths. After the loop is closed,
we perform a smoothing operation, which creates a polyline that
is defined on the mesh through barycentric coordinates. Since the
different poses have a corresponding mesh structure, the defined
boundaries are valid for all poses (Fig. 4 (a)-(c)). We can create a
garment from these boundaries by specifying a boundary-enclosed
region on the avatar. To define the initial garment rest shape we
duplicate the enclosed submesh and remesh it to a desired resolution,
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Our toolset allows creating garment boundaries on the avatar mesh by connecting clicked vertices on a shortest path (a). These boundaries are then smoothed (b) and expressed in barycentric coordinates on the triangle mesh, which allows us to transfer them to different poses (c). Clicking an area on the avatar mesh creates a garment mesh enclosed by the created boundaries (d). Garments can be extended with loose-fitting parts at a chosen boundary (e). Even during simulation (f), changes to the garment are possible. We allow painting areas where cloth should be added (g,h). All interactions are marked by a cursor.

Extension tool.
In order to allow for the design of dresses, skirts, tops with wide sleeves and similar features that are not skintight, we allow to extend a garment at a chosen boundary. An axis is created from this boundary by calculating its center of mass $c$ and its vector area $a$. The vector area is a vector that is well defined by the vertex positions of the boundary and points in the direction that maximizes the enclosed area when projected onto a plane, and therefore can also be calculated for non-planar boundary loops. The chosen boundary is duplicated, translated and scaled along this axis, such that it lies on an additionally specified point, which can be defined with a mouse click by the user. The duplicated boundary is then connected to the existing garment mesh. A remeshing operation ensures even meshing. See Fig. 4 (e).

Paint tool.
This tool can be used to specify areas that need to be enlarged. The intensity of the color per triangle defines a scaling factor. The garment mesh is then adjusted accordingly by applying the methods described in Sec. 3.4. See Fig. 4 (g)-(h).

Comfort tool.
We allow the user to set a minimum offset distance between the garment and the body. When the garment is simulated (Sec. 3.3), a simple collision detection with the body pushes the garment vertices away from the body by the set distance and creates a small stretch everywhere. The rest shape adjustment step (Sec. 3.4) then automatically adjusts the garment to counteract this stretch. A small offset is useful to allow for thick textiles or to compensate small errors introduced through the 3D scanning process. Large offsets can also be used as a design choice. See Fig. 5.

Pinning tool.
We allow the user to pin selected vertices of the garment mesh to the body during the cloth simulation, specifically whole garment boundaries. The pinning is implemented as an additional constraint (Sec. 3.3). This tool is especially useful when generating triangles with similar area (Fig. 4 (d)). This tool is used to create a new garment shape, whereas all following tools are used to edit existing garment shapes.

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the avatar moves through different poses. As illustrated in Fig. 6, a garment’s neckline might stretch when the avatar lowers its arms. Pinning the neckline prevents this enlargement and keeps the neckline of the rest shape in place.

**Seam tool.** After the final garment shape is computed by moving through several poses and ranges of motion, we allow to optionally redefine seams by creating boundaries, similar to the **Boundary tool**, but directly on the garment rest shape. This is not necessary, but might be desired to give the garment a certain look, e.g., by defining traditional shoulder seams for men’s shirts (Fig. 10, 11, 13) or by creating seams between regions with different textiles (Fig. 14).

To design a garment, we can choose an arbitrary pose as a starting point, as long as this pose has no self-overlaps. Poses with arms held at the sides often have self-overlaps below the shoulders, which leads to self-intersections in the garment created from this pose. Such self-overlaps often do not untangle during the cloth simulation, even if the arm is lifted or the cloth stretched. The choice of pose used for designing the initial shape of the garment influences the final shape, and one can achieve different designs, as we discuss further in Sec. 4. Additionally to the tools above, our systems allows the user to load any existing garment mesh to work with.

### 3.3 Cloth simulation

After designing the initial shape of a garment, we simulate its draping on the avatar with respect to its 3D rest shape. In this section, this garment rest shape is equal to the initial shape design and does not change. As soon as the avatar moves through different poses though, we allow the rest shape to deform as well to adjust to large stretch forces, as described in Sec. 3.4.

We use a standard cloth model that treats bending, stretching and shearing models separately [Baraff and Witkin 1998; Bridson et al. 2005]. Similarly to previous work [Umetani et al. 2011], we use the isometric bending model [Bergou et al. 2006], which is efficient in terms of computation time, since it has a constant positive semi-definite energy Hessian. This model penalizes out of plane angles between neighbouring triangles. Even though we are working with a 3D rest shape where this is not the case, most materials used to fabricate the final garment are flat, motivating our choice of bending energy. Alternatively, a more computationally involved bending energy can be used, such as penalizing the deviation of angles from the rest shape, based on the work by Tamstorf et al. [2013].

As has been described in [Umetani et al. 2011], compression in the cloth can induce instabilities in the usual St. Venant-Kirchhoff (StVK) constant strain triangle (CST) due to an indefinite force Jacobian [Volino et al. 2009]. Therefore we use a stabilized StVK CST by eliminating negative eigenvalues in the Jacobian when the element is under compression, similar to [Teran et al. 2005].

Whenever the user specifies boundaries that are to be pinned onto the body with the **Pinning tool**, we add additional constraints to the cloth simulation. We find that incorporating the constraints via mass modification, as described in [Baraff and Witkin 1998], introduces large stretch forces in the triangles adjacent to the fixed boundaries, which interferes with the later rest shape adjustment that is based on stretch. Instead, we introduce penalty forces, keeping the garment boundary vertices close to the defined boundaries. The corresponding condition \( C \) is defined as:

\[
C(X) = \|x_i - b_i\|^2, \tag{1}
\]

where \( X \in \mathbb{R}^{n \times 3} \) contains the coordinates of the simulated garment mesh, \( x_i \) are the vertex positions of the pinned boundaries and \( b_i \) are the corresponding boundary vertex positions on the avatar. Right after garment creation, we create these pairs of vertices by associating the garment boundary vertices \( x_i \) with their closest point on the avatar mesh \( b_i \), which we represent in barycentric coordinates. As the avatar moves, this target position changes and is also offset in the normal direction from the avatar mesh by the **Comfort control distance**.

We use a simple collision detection of the garment with the avatar by calculating a signed distance for each garment vertex to the avatar mesh. We resolve collisions by moving the garment vertices along the normal, which is calculated at the closest point on the avatar mesh by the **Comfort tool** by moving the vertex by the specified offset away from the avatar mesh. Since the collision detection operates solely on the vertices, a dense enough mesh resolution of the garment is essential to avoid scenarios where arms slip through the garment mesh.

Many avatar poses can exhibit self-intersections, for example below the armpits when the arms are held close to the body. We observe that these self-intersections can induce instability in the cloth simulation, especially when there is an offset defined between the garment and the avatar. This is due to collisions not being adequately resolved. We deal with these problem regions by assuming that ideally, the cloth would get stuck between the two opposing surfaces in these areas. Therefore, we detect all vertices affected by self-intersection regions during the collision detection step. We then mark these as fixed during the simulation and add additional constraint forces equivalent to Eq. (1).
3.4 Rest shape adjustment

Our system features automatic adjustment operations that adapt the garment to fit a specific dynamic avatar, which is moving through a set of poses (see Fig. 7). This way we can ensure a good fit for many everyday situations that would otherwise introduce significant stretch. This can be seen, for example, in a long-sleeved shirt in Fig. 10, designed for a T-pose (arms are outstretched to the side). When the avatar lowers the arms, there is not enough cloth atop the shoulders, so that stretch is high in that region, resulting in a bad fit and a risk of eventually tearing the garment. We detect such situations by monitoring per-triangle stretch while the avatar is moving through a set of scanned input poses, as described in Sec. 3.1. The user can optionally introduce manual edits to the garment that are not directly related to fit, like puffy sleeves.

Per triangle stretch. Garment mesh adaptions are defined locally, since reducing stretch can be expressed per mesh element. We follow the basic methodology of gradient domain processing [Botsch and Sorkine 2008], similar to as-rigid-as-possible mesh editing [Sorkine and Alexa 2007] to deform the current rest shape \( X \in \mathbb{R}^{n \times 3} \) with \( n \) vertices in order to reflect the desired changes expressed w.r.t. the current simulation mesh \( X \in \mathbb{R}^{n \times 3} \). To this end we alternate the modification of individual triangles with stitching them into a consistent mesh by solving a Poisson system. The coordinates of each rest shape and simulation triangle are given respectively by

\[
\hat{x}_t = (\hat{x}^0_t \; \hat{x}^1_t \; \hat{x}^2_t) \in \mathbb{R}^{3 \times 3}, \quad x_t = (x^0_t \; x^1_t \; x^2_t) \in \mathbb{R}^{3 \times 3}.
\]

Each triangle \( x_t \) can be rigidly transformed such that it is contained in the 2D plane and its first vertex coincides with the origin. The two vectors spanning this triangle form the \( 2 \times 2 \) matrix \( P_{x_t} \) (see Fig. 8). This matrix is invertible whenever the triangle \( x_t \) is non-degenerate. In order to measure stretch, we first construct the deformation gradient \( F \in \mathbb{R}^{2 \times 2} \), which can be conveniently expressed using the \( 2 \times 2 \) matrix representation:

\[
F = P_{x_t} (P_{x_t})^{-1}.
\]  (2)

The deformation gradient exists and is invertible if the simulation triangle \( x_t \) and the rest shape triangle \( \hat{x}_t \) are both non-degenerate.

Moreover, given an invertible deformation gradient, we can map between the projected 2D rest shape and simulation triangle shape. We use this property to adapt the rest shape such that the simulation triangle exhibits less stretch. The eigenvalues of the right Cauchy-Green tensor \( F^T F \) are the squared principal stretches \( s_1^2 \) and \( s_2^2 \). Consequently the singular values of the deformation gradient \( F \) are given by the principal stretches:

\[
F = U \begin{pmatrix} s_1 & 0 \\ 0 & s_2 \end{pmatrix} V^T.
\]  (3)

Reference triangle adaption. Our goal is to find a rest shape such that the stretch is within a certain range \([0, 1 + \delta]\). A stretch value above 1 means the cloth exhibits stretch, and a value below 1 indicates compression. Our simulation always starts with a fitting garment for one specific pose. Therefore we never want to decrease triangle area, lest we destroy the fit. Hence, a threshold \( \delta \) is only needed to limit stretch, but not compression. To find new reference triangles \( P_{x'_t} \) that meet our criteria locally, we keep the triangle of the simulated garment fixed and modify the principal stretches

\[
s'_1 = \frac{s_1}{\beta_t}, \quad s'_i = \frac{s_i}{\beta_t} < 1 + \delta
\]

\[
1 + \delta, \quad \text{otherwise.}
\]

By limiting the principal stretches and setting them to smaller value \((s'_i < s_i)\), we force the rest shape triangle to become larger accordingly. Additionally, we can manually enforce a larger rest shape triangle by dividing by a user defined local scaling factor \( \beta_t > 1 \). Using the Paint tool, the user can add fabric by directly marking regions of the simulated mesh using a sketch-based interface. By modifying the brush intensity the amount of fabric that should be introduced in a specific area can be controlled. Our system translates this input into the local scaling factor \( \beta_t \) for each mesh triangle and uses it to adapt the rest shape. The initial value for triangles that are not manually enlarged is \( \beta_t = 1 \).

We modify the singular value decomposition of \( F \) to find the deformation gradient that is close to the original one while being consistent with the modified principal stretches:

\[
F' = U \begin{pmatrix} s'_1 & 0 \\ 0 & s'_2 \end{pmatrix} V^T.
\]  (4)

We can also directly construct the inverse of this matrix

\[
(F')^{-1} = V \begin{pmatrix} 1/s'_1 & 0 \\ 0 & 1/s'_2 \end{pmatrix} U^T.
\]  (5)

Using this new deformation gradient, we can conveniently find two vectors spanning the corresponding projected rest shape triangle:

\[
y'_t = (y^0_t \; y^1_t) = (F')^{-1} P_{x'_t}.
\]  (6)

Rest shape update. The previous step yields individual, 2D reference triangles that are compatible with the requirements on stretch. In order to obtain a modified rest shape \( \hat{X}' \), these triangles have to be stitched to form a consistent triangle mesh given by the set of triangles \( T' \) and coordinates \( \hat{y}'_t \). To this end, we employ Poisson based stitching using the cotan Laplacian, akin to as-rigid-as-possible

Fig. 8. The deformation gradient relates the triangles of the rest shape and the simulated garment.
we opted to create all example garments by generating sewing with respect to the new rest shape positions of the previous rest shape (see Fig. 9). The objective is optimized This method parameterizes surfaces over flat domains by directly sewing pattern pieces (e) back together.

along with the same dress (f) generated from stitching the individual introducing only a very small amount of distortion across all our that nicely approximate the rest shape. We found that the flattening and Crane 2018, even short cuts can yield sewing pattern pieces clustering, choose a length normalization weight of

optimizing the distortion induced by cutting and flattening. As

achieving good results with

\[ n \]

improves computation time. We observe that we can

steps of cloth simulation based on a fixed rest shape deformation [Sorkine and Alexa 2007]. This amounts to minimizing the objective function

\[
E(R, X') = \sum_{t \in T} \sum_{k=1,2,3} \cot \alpha_{t,k} \left( \| (\hat{x}'_t)_i - (\hat{x}'_t)_{i-1} - R_t y'_t \|^2 \right) 
\]

with respect to the new rest shape positions \( \hat{X}' \) and the per triangle rotations \( R \). Here \( i \) and \( j \) refer to the vertices of the \( k \)-th edge of triangle \( t \) and \( y'_t \) denotes the corresponding edge of the reference triangle \( y_t \). The matrix \( R_t \in \mathbb{R}^{3 \times 2} \) represents a rotation from the 2D plane into 3D and \( \alpha_{t,k} \) is the angle opposite of edge \( k \) in triangle \( t \) of the previous rest shape (see Fig. 9). The objective is optimized by alternating minimization with respect to \( R \) and \( X' \).

Our overall pipeline consist of repeatedly adjusting the avatar fabric mesh, followed by \( n \) steps of cloth simulation based on a fixed rest shape and a final step of adjusting the rest shape while the simulated cloth is fixed. Computing several steps during the cloth simulation allows the garment to settle on the slightly adjusted avatar pose before we calculate the stretch to adjust the rest shape. At the same time, a small \( n \) improves computation time. We observe that we can achieve good results with \( n = 6 \).

3.5 Garment fabrication

After the final rest shape of the garment is computed, we use it as a basis for further production. In principle, users can choose any fabrication method that suits their needs, such as creating seamless knitting patterns using the method of Wu et al. [2019]. In this paper, we opted to create all example garments by generating sewing patterns through variational surface cutting [Sharp and Crane 2018]. This method parameterizes surfaces over flat domains by directly optimizing the distortion induced by cutting and flattening. As suggested in this work, we employ the Hencky energy, which is useful for physical fabrication. We weigh this energy against the cut lengths to balance the number of sewing pattern pieces versus the introduced distortion. We initialize the pattern through normal clustering, choose a length normalization weight of 5 and Hencky distortion weight of 10 and take 500 steps. As was shown in [Sharp and Crane 2018], even short cuts can yield sewing pattern pieces that nicely approximate the rest shape. We found that the flattening introduces only a very small amount of distortion across all our examples. In Fig. 12 we show an optimized and simulated dress (b) along with the same dress (f) generated from stitching the individual sewing pattern pieces (e) back together.

4 RESULTS

Our implementation is based on several existing libraries: libigl [Jacobson et al. 2018], PMP [Siegler and Botsch 2020], OpenMP [Dagum and Menon 1998] and Cholmod [Chen et al. 2008]. For Figures 4, 5 and 6 we use avatars from the FAUST dataset [Bogo et al. 2014]. All other avatars have been scanned by us. We use a computer with a 12-core 2.7 GHz CPU and 64 GB memory.

The dress shown in Fig. 14 takes approximately 2.8 minutes to adjust to the two additional poses. Computation times vary mainly due to the varying number of poses and garment resolution. In Table 1 we report average frame rates for all modeling sessions presented in this paper. Our algorithm is implemented by augmenting a traditional Newton-based simulation framework, which is responsible for the bulk of computation time. Running the simulation without adapting the garment results in the performance reported under "fps (sim)"; the full algorithm runs at a frame rate of "fps (full)". Consequently, any method accelerating the chosen type of cloth simulation technique immediately benefits our algorithm. The frame rate of our interactive application largely depends on the garment mesh resolution reported as the number of vertices.

For all examples shown in this paper we use the same cloth parameters, chosen to simulate textiles that practically do not stretch in order to highlight the capabilities of our method, as they require the largest adjustments to the rest shapes. However, our method works with any kind of textile, if the cloth simulation parameters are chosen accordingly. We use the stiffness constants \( k_{\text{stitch}} = 800 \), \( k_{\text{shear}} = 200 \) and \( k_{\text{bend}} = 10^{-6} \) and the damping stiffness constants \( k_{\text{d,stretch}} = 100 \), \( k_{\text{d,shear}} = 1 \) and \( k_{\text{d,bend}} = 10^{-5} \) for the stretch, shear and bend constraints, respectively (for details we refer to [Baraff and Witkin 1998]). We advance the simulation with a time step of \( \delta = 0.0025 \) and adjust the rest shape every 8 time steps with a stretch threshold of \( \delta = 0.1 \). We move through 60 interpolation steps between two poses. We empirically found these parameters to consistently yield good results, however, any other set of parameters might be chosen in order to achieve a different trade off between accuracy and performance.

We created several garments and computed the sewing patterns as detailed in Sec. 3.5. All are sewn by professional tailors. We list the design parameters for the individual garments in Table 2.

Men’s shirt. We created two men’s shirts for the same person. The first one, shown in Fig. 10, is created from a single T-pose, while

| Figure | #vertices | fps (full) | fps (sim) |
|--------|-----------|------------|------------|
| Fig. 1 | 1103      | 7.82       | 8.29       |
| Fig. 13 | 3926      | 1.70       | 1.74       |
| Fig. 14 | 4270      | 1.76       | 1.81       |
| Fig. 10 | 3032      | 3.75       | 4.00       |
| Fig. 11 | 3032      | 3.69       | 3.94       |
| Fig. 12 | 1484      | 5.73       | 6.00       |
| Fig. 15 | 3597      | 3.32       | 3.54       |
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Fig. 10. Starting from a single T-pose (a), we create the shape of a shirt (b) and its sewing pattern (c). This shirt fits perfectly in the T-pose, but creates uncomfortable stretch in other poses (d). Especially when the arms are held at the sides, visible stress is produced on the buttons of the shirt. This is also noticeable for arms outstretched to the front and up (e).

Fig. 11. Starting from the same shirt design for the T-pose as in Fig. 10, we now move through five different poses (a) to update the rest shape of the garment (b) and create a sewing pattern for fabrication (c). We show the final digital garment on all five poses (e), as well as the sewn shirt (f). The shirt accommodates all five poses, and no uncomfortable stretch occurs (d).

the second one is based on five different poses shown in Fig. 11, starting from the T-pose. For both shirts we use the Boundary tool to create the shape of the garment and add an offset of 1.5 cm with the Comfort tool. While moving through the different poses to adjust the rest shape, we pin the collar and cuffs with the Pinning tool to ensure that the fabric of the sleeves is stretched sufficiently instead of being pulled back when moving the arms. Finally, we pre-define the shoulder seams and button border typical for shirts with the Seam tool. The sewing pattern is then created from this pre-cut mesh (here we use a Hencky distortion weight of 3 to create fewer seams). A professional tailor added the collar, cuffs and button border. A comparison of both shirts (Fig. 10 (d) and Fig. 11 (e)) shows that the shirt created solely from the T-pose fits in this specific pose and stretches uncomfortably in other poses, close to tearing. The second shirt allows a wider range of motions. Fig. 2 shows additional photographs of the second shirt and compares to an off-the-shelf, standard shirt bought in a store for the same person. Both shirts take approximately 7 hours to fabricate, including the cutting of the cloth, sewing and adding the cuffs, collar and buttons. According to the tailors we worked with, the production time for garments depends mostly on the number of pieces and the length of the seams. Therefore they estimate that the production time for our shirt and a standard one would not differ significantly.

Maternity wear. Our method can also be used to make garments for special body shapes. We create a dress that fits during pregnancy and afterwards (Fig. 12), starting from the slim shape. After the rest shape adjustment from the slim shape to the pregnant one, we
Our method can be used to create garments that fit during and after pregnancy. Instead of different poses, we start from different scanned body shapes (a). We design the initial dress shape on the slim pose (c), compute its adjustment to both poses to get the final shape (d) and create a sewing pattern (e). Comparison of the draped final rest shape on both poses (b) with the sewn and draped pattern (f) reveals only negligible difference. The sewn garment (g) can be worn during and after pregnancy.

Figure 12. Our method can be used to create garments that fit during and after pregnancy. Instead of different poses, we start from different scanned body shapes (a). We design the initial dress shape on the slim pose (c), compute its adjustment to both poses to get the final shape (d) and create a sewing pattern (e). Comparison of the draped final rest shape on both poses (b) with the sewn and draped pattern (f) reveals only negligible difference. The sewn garment (g) can be worn during and after pregnancy.

By creating a jumpsuit, we show that our method can handle complex cases of larger garments that cover the whole body (Fig. 15). We again use the Boundary tool to define the upper part of the jumpsuit, and the Extension tool to create the legs. Starting from the A-pose with half-raised arms at the sides, we move through 4 poses, while pinning the collar and cuffs with the Pinning tool and adding an offset of 1 cm with the Comfort tool. Using the Seam tool, we create a straight seam in the back for a zipper. Fabricating the denim jumpsuit takes 14 hours, where half of the time is used to create the elaborate seaming.

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Inclusive garment design. The strength of our method is showcased by creating garments for people who fall far outside the standard sizes available in stores, see Fig. 1. In this example, imperfections in the registered avatars for the different poses do appear, especially around the hands and feet, likely due to the SMPL model not being trained on such body shapes. Still, our method is robust to small scan errors, and we can still design a custom-fit dress.

We show two additional simple results, created from just two poses: a shirt (Fig. 13) and a white dress (Fig. 14), to highlight the variety of possible garments. The shirt in Fig. 13 is designed in the same way as the previous shirt from Fig. 11. The white dress is created similarly to the pregnancy dress from Fig. 12, but we use the Seam tool to cut a strip of cloth that is replaced by a red band. By calculating the underlying garment shape, but allowing the professional tailor to add small details like buttons, trims and collars, a diverse set of garments can be created.

Discussion. The choice of the initial pose plays a vital role in the final garment shape, as the garment exhibits the least amount of folds in this pose. The further the avatar moves away from that pose, the more folds can be expected. This can be seen when comparing the shirt in Fig. 11, which is designed for the T-pose, and the shirt in Fig. 13, which is designed for the A-pose. There is a tradeoff between fit and movement range that has to be considered when using our system. The more poses the garment needs to fit tightly in, the less the garment can fit each individual pose. For example, traditionally designed shirts usually do not accommodate a pose...
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(a) (b) (c) (d)
(e) (f)

Fig. 15. The jumpsuit constitutes a challenging full-body example, where we use four poses as input (a). Note that in the first pose the arms are lowered halfway at the sides, whereas in the last pose the arms are held halfway to the front. We use our toolset to create an initial garment (b) and compute the adjustment of the rest shape to all four poses (c), which we drape on all four avatar poses (e) and use to create a sewing pattern (d). The physical jumpsuit fits all poses comfortably (f).

with arms raised high above the head. By discarding this pose, we can achieve a tighter fit with a limited movement range, which most people are already accustomed to.

5 CONCLUSION

We presented a method to design and optimize the shape of a garment for a range of 3D scanned poses, such that the garment fits comfortably but tightly in all poses. We demonstrated the capabilities of our method by sewing different garments for a range of individual body shapes.

Limitations. Since the input of our method is a number of registered 3D scans, we are limited by the current state of the art in human body model capture. This becomes apparent when we scan people with proportions strongly deviating from the average, as can be seen in Fig. 1, where difficulties in registering the scans result in elongated hands and misplaced heels arise. In theory, we could design garments for people with missing extremities, but current methods based on SMPL [Loper et al. 2015] would hallucinate these extremities, requiring manual fixing of the body meshes. The same registration process also creates self-intersections in the avatars, leading to problems in cloth simulation and precluding the usage of self-intersecting poses as the initial poses for designing a garment.

Future work. Currently, the final shape of the garment depends on the sequence of poses and especially on the initial one. Though this gives designers the option to choose a main pose in which the garment is worn, creating a garment independent from the simulation sequence might consider the poses more equally. Furthermore, we initiate the rest shape of the garment from the body shape of the initial pose and do not take the draping effect into account in this first step. Generating the initial rest shape such that it physically deforms into a tight fit could slightly improve our method in larger convex areas, like under breasts and the bottom.

Our method only allows for the body to influence the garment shape, but not vice versa. In the future, we would like to incorporate the physical simulation of body tissue to simulate the influence of the garment on the body. Especially in tight areas, body tissue can be visibly displaced by the garment. Incorporating recent work in body modeling, like the dynamic body model Dyna [Pons-Moll et al. 2015] or the STAR model [Osman et al. 2020], would be a first step in that direction. We would also like to improve the simulation by incorporating cloth parameters measured from real textiles. Incorporating friction into the simulation would further improve the design of pants or skirts to prevent rubbing against the skin and sliding.

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Table 2. Statistics for all garments.

| Figure | faces | poses | initial pose | tools | offset | textile | pieces | sewing time | model height |
|--------|-------|-------|--------------|-------|--------|---------|--------|-------------|--------------|
| Shirt T-pose | 10 | 6 | 1 | T-pose | 1.46 | 1.5 cm | cotton poplin | 11 | 7 h | 190 cm |
| Shirt | 2, 11 | 6 | 5 | T-pose | 1.45,6 | 1.5 cm | cotton poplin | 10 | 6.5 h | 190 cm |
| Jumpsuit | 15 | 7 | 4 | A-pose | 1.2,4,5,6 | 1.0 cm | denim | 17 | 14 h | 163 cm |
| Pregnancy dress | 12 | 4 | 2 | pre-pregnancy | 1.2,3,4 | 0.8 cm | lyocell | 7 | 3 h | 172 cm |
| Yellow dress | 1 | 5 | 5 | T-pose | 1.2,4,5,6 | 0.5 cm | lyocell | 13 | 2.75 h | 125 cm |
| White dress | 14 | 9 | 2 | A-Pose | 1.2,4,6 | 0.5 cm | polyester crepe | 9 | 3 h | 177 cm |
| Blue Shirt | 13 | 8 | 2 | A-Pose | 1.2,4,6,10 | 1.0 cm | cotton poplin | 8 | 4.5 h | 188 cm |

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