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Computational Design of Body-Supporting Assemblies

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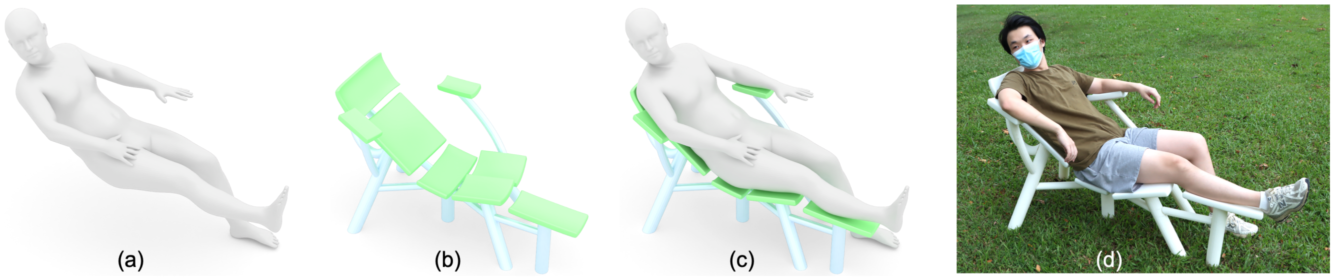

Figure 1: *Taking (a) a human body in a specific posture as input, we present a computational approach to designing (b) a body-supporting assembly that (c) fits the body posture to make the assembly comfortable to use. We validate the usability of our designed body-supporting assembly by conducting (d) an informal user study with a 3D-printed full-scale prototype.*

Abstract

A body-supporting assembly *is an assembly of parts that physically supports a human body during activities like sitting, lying, or leaning. A body-supporting assembly has a complex global shape to support a specific human body posture, yet each component part has a relatively simple geometry to facilitate fabrication, storage, and maintenance. In this paper, we aim to model and design a personalized body-supporting assembly that fits a given human body posture, aiming to make the assembly comfortable to use. We choose to model a body-supporting assembly from scratch to offer high flexibility for fitting a given body posture, which however makes it challenging to determine the assembly's topology and geometry. To address this problem, we classify parts in the assembly into two categories according the functionality:* supporting parts *for fitting different portions of the body and* connecting parts *for connecting all the supporting parts to form a stable structure. We also propose a geometric representation of supporting parts such that they can have a variety of shapes controlled by a few parameters. Given a body posture as input, we present a computational approach for designing a body-supporting assembly that fits the posture, in which the supporting parts are initialized and optimized to minimize a discomfort measure and then the connecting parts are generated using a procedural approach. We demonstrate the effectiveness of our approach by designing body-supporting assemblies that accommodate to a variety of body postures and 3D printing two of them for physical validation.*

CCS Concepts
• ***Computing methodologies*** → *Shape modeling;*

1. Introduction

Body-supporting shapes are designed to physically support a human body during activities like sitting, lying, or leaning. These shapes, such as chairs, are typically designed in standardized forms to address general functional needs by accommodating common body postures and shapes. With recent advances in digital fabrication, there is growing interest in designing body-supporting shapes in *personalized forms*. Such body-supporting shapes are able to accommodate to specific body postures and shapes, thus increasing comfortability when a person makes use of these shapes.

Existing works [LBRM18, LWOM20] model personalized body-supporting shapes as a continuous freeform surface that fits a given body posture, aiming to maximize comfortability by distributing the pressure uniformly on the body. However, the modeled body-supporting surface forms a large, monolithic piece of geometry, bringing at least two disadvantages. First, the large body-supporting surface significantly increases the cost and time to real-

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ize it via digital fabrication. Second, the fabricated bulky surface not only occupies more space during usage, but also hinders transportation and storage.

In this paper, we propose to model a body-supporting shape as an assembly of parts with relatively simple geometry. We call it the *body-supporting assembly*; see Figure 1(b&c) for an example. Such an assembly reduces the fabrication cost and time, and facilitates transportation, storage, and maintenance, as practiced by many real-world furniture designs. Different from existing data-driven approaches [ZLDM16, FCSF17], we choose to model a body-supporting assembly from scratch to offer high flexibility for fitting a given body posture. However, this research problem is non-trivial. First, we need to determine the topology of the assembly, including the number of parts and how these parts are connected. Second, we need to compute the geometry of each part, especially for these parts that directly support the human body to make the assembly comfortable to use.

In this paper, we propose a computational approach to modeling and designing personalized body-supporting assemblies. At the modeling stage, we classify all the parts into two categories: supporting parts and connecting parts, where the supporting parts fit different portions of the body and the connecting parts connect all the supporting parts to form a stable structure. We also propose a geometric representation of the supporting parts such that they can have a variety of shapes controlled by a small number of parameters. At the design stage, we present an approach for designing a body-supporting assembly to fit a given body posture, aiming to make the assembly comfortable to use by that person. In particular, we first determine the number of supporting parts and initialize their spatial placement by analyzing portions of the body that need support, and then optimize the geometry, size, and spatial placement of these parts to minimize a discomfort measure while ensuring fabricability of the assembly. Next, we generate connecting parts using a procedural approach, resulting in a body-supporting assembly that is ready for fabrication and usage.

Overall, we make the following technical contributions:

- We propose a method to model the topology, parameterize the geometry, and evaluate the discomfort of body-supporting assemblies; see Section 3;
- We present an optimization-based approach for designing a personalized body-supporting assembly that fits a given body posture and is ready for fabrication; see Section 4.

We demonstrate the effectiveness of our approach by designing body-supporting assemblies that accommodate to a variety of body postures and shapes. We validate the usability of our designed body-supporting assembly by conducting an informal user study with a 3D printed full-scale prototype; see Figure 1(d). The code and data of this paper are available at `https://github.com/abcqmars/Body2Assembly`.

2. Related Work

Computational design of furniture assemblies. Recently, the graphics community has a growing interest in research on computational design of furniture assemblies for digital fabrication [WSP21]. A variety of computational methods and tools have been developed for designing furniture with certain characteristics, including fabricability for physical realization [LOMI11, KHLM17, YZM23], structural stability for the usage [UIM12, FSY*15, YKGA17], foldability for saving space [LHAZ15, IY18], and reconfigurability for multiple functionalities [SFJ*17, FZLF24, ZC18]. Following this line of research, we study computational design of personalized body-supporting furniture assemblies and focus on the functionality. In particular, we aim to design a body-supporting furniture assembly such that a person feels comfortable when he/she sits/lies on the furniture in a specific body posture.

Modeling body-supporting shapes. Research in modeling body-supporting shapes aims to find shapes that match a given human body to support it ergonomically. Novel user interfaces have been developed to model body-supporting shapes, including a sketch-based interface for designing chairs with planar parts for laser cutting [SLMI11], and an augmented reality interface for personalizing furniture by using poses, gestures, and speech commands as the user input [LCMS16].

Researchers in the graphics community address the problem by focusing on the pose-inspired shape modeling. Zheng et al. [ZLDM16] presented an approach for reshaping body-supporting objects to fit a user-specified body and pose for accommodating ergonomics constraints. Fu et al. [FCSF17] proposed an approach to synthesize multi-function shapes that fit a user-specified body and pose by combining parts from objects of different categories. With the recent advance in digital fabrication, some research works focus on modeling body-supporting surfaces for personalized fabrication. Leimer et al. [LBRM18] proposed a computational tool for designing a body-supporting surface that nestles to the shape of a given body posture in order to make the human feel comfortable. Leimer et al. [LWOM20] later extended the approach with an improved physical model of sitting for computing pressure distribution to evaluate comfortability. Zhao et al. [ZLC*22] proposed an approach to designing a body-supporting surface that maximizes the ergonomics of physically based contact between the rigid body-supporting surface and a part (e.g., buttocks, foot) of a deformable human model.

Different from [ZLDM16, FCSF17] that rely on a collection of existing 3D models for modeling body-supporting shapes, we propose to model body-supporting shapes from scratch, providing higher flexibility for fitting a given body posture. Compared with [LBRM18, LWOM20] that model a body-supporting shape as a large, monolithic freeform surface, we propose to model a body-supporting shape as an assembly of parts with relatively simple geometry, offering a more practical and cost-effective way to fabricate and use the shape for body supporting.

Surface decomposition. Surface decomposition aims to decompose a large surface into a number of small patches for different objectives, including texture mapping [SSGH01], metamorphosis [STK02], rationalization [EKS*10], and fabrication [ZLZ*23]. Different from these works, we approximate a body surface using a small number of body-supporting parts with simple shape, aiming to make the resulting assembly comfort to use and easy to fabricate.

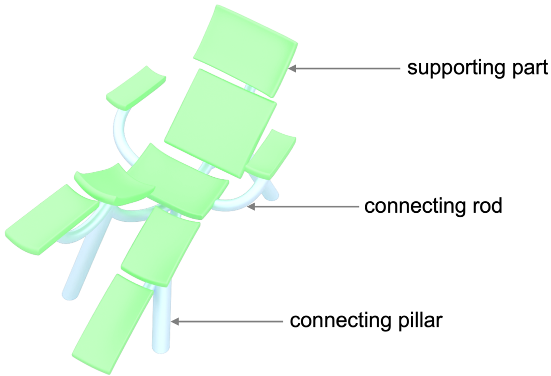


Figure 2: *We model a body-supporting assembly as an assembly of body-supporting parts (in green color), connecting pillars (in blue color) that stand on the ground, and connecting rods (in blue color) that connect supporting parts and connecting pillars.*

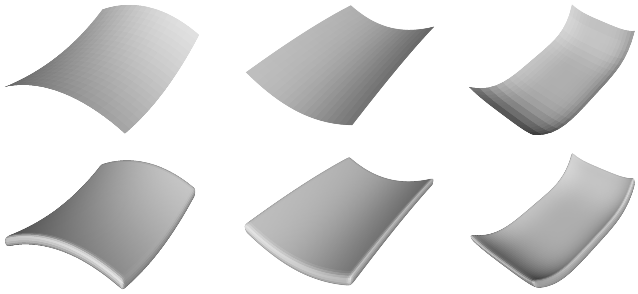


Figure 3: *We model the geometry of each supporting part using a generalized hyperbolic paraboloid. This geometric representation allows to model supporting parts with (left) saddle-, (middle) cylinder-, and (right) bowl-like shapes.*

3. Modeling Body-Supporting Assemblies

In this section, we first formulate the problem of modeling and designing personalized body-supporting assemblies. Next, we introduce an approach to model the topology and geometry of body-supporting assemblies. Lastly, we describe a method to evaluate the discomfort of body-supporting assemblies.

Problem formulation. Our input is a human body with a given posture represented by a mesh; see Figure 1(a). Our goal is to model and design a body-supporting assembly that fits the given body posture while satisfying the following requirements; see Figure 1(b&c).

1. *Body comfort.* The body-supporting assembly should make the human feel comfortable when he/she sits/lies on the assembly with the given posture.
2. *Fabricability.* The body-supporting assembly should be fabricable, e,g., by 3D printing. This means that its component parts should be fabricable and can be assembled without collision.
3. *Material efficiency.* The body-supporting assembly should minimize material usage, to reduce fabrication cost and save space.

Modeling topology of body-supporting assemblies. The topology of a body-supporting assembly is about parts in the assembly and their connections. We classify parts in the assembly into two categories according to the functionality.

- *Supporting parts*. Body-supporting parts (abbreviated as supporting parts) are used to support different portions of a human body, determining the comfortability of using the assembly by the human; see the green parts in Figure 2.
- *Connecting parts*. Structure-connecting parts (abbreviated as connecting parts) are used to connect all the supporting parts to form a stable and thus usable structure; see the blue parts in Figure 2. There are two types of connecting parts:
  - *Connecting pillars*. A connecting pillar connects a supporting part (e.g., one that supports the back or thigh) directly to the ground, enabling the body-supporting assembly to stand on the ground by itself; see the thick blue parts in Figure 2.
  - *Connecting rods*. We assume there is no direct connection between any pair of supporting parts as well as any pair of connecting pillars. The goal of connecting rods is to connect supporting parts and connecting pillars, making the assembly structurally stable; see the thin blue parts in Figure 2.

Modeling geometry of supporting parts. We model the geometry of each supporting part P_i as a shell by thickening a base surface S_i along the direction opposite to the surface normal and then rounding the edges; see Figure 3. Following the practice in ergonomic furniture design discipline [LM20, TH], we model the base surface as a hyperbolic paraboloid, augmented with two fourth-order terms

$$S_i(a_i, b_i, c_i, d_i) = a_i x^2 - b_i y^2 + c_i x^4 + d_i y^4, \quad x \in [-L, L], \; y \in [-L, L] \tag{1}$$

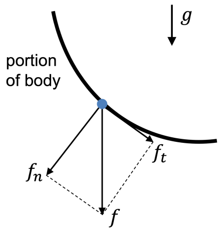
where $\{a_i, b_i, c_i, d_i\}$ are the parameters that control the shape of the surface, and L is a constant set to 1 by default. In particular, the parameters a_i and b_i control the base curvatures along the x and y directions, respectively, defining the primary saddle-like shape. The parameters c_i and d_i modulate higher-order curvature along the same axes, respectively. In addition, we use another two parameters $\{\alpha_i, \beta_i\}$ to control anisotropic scaling of the surface along the x and y axes, respectively.

A hyperbolic paraboloid naturally forms a saddle-like surface that curves upward in one direction and downward in the other, making it well-suited for distributing pressure evenly when supporting a human body without restricting necessary body movement; see Figure 3 (left). A hyperbolic paraboloid can also model a cylinder-like surface when a_i or b_i is set to 0; see Figure 3 (middle). To increase the variety of shapes that can be modeled, we augmented the standard hyperbolic paraboloid with two fourth-order terms in Equation 1. This augmentation allows to model surfaces that cannot be achieved by the standard hyperbolic paraboloid yet are useful in body supporting such as bowl-shaped surfaces [San13]; see Figure 3 (right).

Modeling geometry of connecting parts. We model the geometry of connecting pillars as a cylinder with a large radius since they should be thick enough to support the weight of the assembly and the human body; see again Figure 2. We model the geometry of each connecting rod as a generalized cylinder, guided by the material efficiency requirement. The spine curve of the generalized cylinder is represented as a Bézier curve, allowing for smooth shape and flexible connection. The cross section of the generalized cylinder is a circle with a fixed radius, usually smaller than the radius of connecting pillars.

Our modeling of the supporting parts, connecting parts, and their connections enables a lightweight and usable body-supporting assembly. In particular, each supporting part can have a variety of shapes and sizes controlled by the four parameters $\{a_i, b_i, c_i, d_i\}$ in Equation 1 and two scaling parameters $\{\alpha_i, \beta_i\}$, providing flexibility to fit a certain portion of a human body for comfortability.

Evaluating body-supporting assemblies. Similar to existing works [LBRM18, LWOM20, ZLC*22], we adopt pressure distribution on a human body as a measure to evaluate the discomfort. To analyze the distribution of forces throughout the human body, we adopt a simple force model in [LBRM18], assuming the body is a rigid object with uniform mass distribution. For each vertex v on the body whose normal $\mathbf{n}_v$ points downward, the gravitational force $\mathbf{f}$ is split into its normal component $\mathbf{f}_n$ and its tangential components $\mathbf{f}_{t_1}$ and $\mathbf{f}_{t_2}$, where $\mathbf{f}_n = (\mathbf{n}_v \cdot \mathbf{f})\,\mathbf{n}_v$; see the inset. Then we estimate the pressure $p(v)$ at each vertex v on the body supported by the assembly using:



$$p(v) = \frac{\|\mathbf{f}_n(v)\|}{A}, \tag{2}$$

where A is the local Voronoi area associated with the vertex v and the resulting p(v) is normalized to the range [0, 1]. Building on the force model, we evaluate the pressure of a supporting part P with base surface S using:

$$E_{\text{pressure}} = \frac{1}{N} \sum_{j=1}^{N} d(v_j, S) \cdot p(v_j), \qquad \text{s.t.} \quad d(v_j, S) > 0 \tag{3}$$

where v_j is a vertex on the human body supported by the part P, $p(v_j)$ is the pressure at the vertex v_j, and $d(v_j, S)$ is the shortest signed distance from vertex v_j to the base surface S. Note that a supporting surface cannot perfectly contact the body since the surface is rigid and its shape is not arbitrary freeform (i.e., subject to Equation 1). Hence, we use the distance $d(v_j, S)$ to weight the pressure $p(v_j)$ in Equation 3 based on an observation that a body region that is not closely supported should contribute more to the discomfort.

Besides pressure on the body, it has been well observed that unintentional sliding off from a body-supporting shape caused by the gravity makes people uncomfortable [RTdZ09]. The sliding issue happens since the normal of the body-supporting shape deviates too much from the opposite of the gravitational direction. Hence, we propose to measure the sliding issue of a supporting part P with base surface S by using:

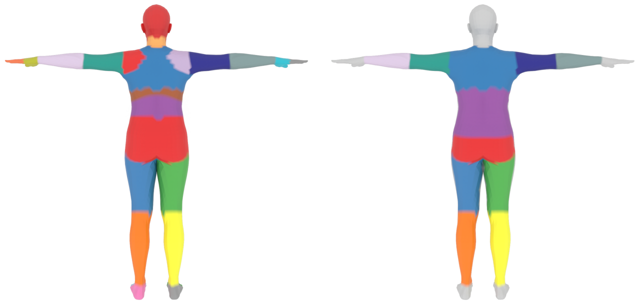


Figure 4: *(left) The SMPL model divides the human body into 24 semantic regions. (right) We filter out regions (e.g., palms, soles, and head) that usually do not require support and merge several small regions at the back of the body, resulting in 11 regions of the body that potentially need supporting.*

$$E_{\text{sliding}} = \frac{1}{M} \sum_{i=1}^{M} \left(1 - \mathbf{n}(v_i) \cdot (-\mathbf{g})\right)^2, \tag{4}$$

where v_i is a vertex on the base surface S, $\mathbf{n}(v_i)$ is the unit surface normal at vertex v_i, and $\mathbf{g}$ is a unit vector representing the gravitational direction.

A supporting part is considered to be uncomfortable to use if it has a large E_{pressure} and a large E_{sliding}. Hence, we linearly combine these two terms to measure the discomfort of a supporting part P_i:

$$E^i_{\text{discomfort}} = \omega_1 E^i_{\text{pressure}} + \omega_2 E^i_{\text{sliding}}, \tag{5}$$

where ω_1 and ω_2 are set as 0.7 and 0.3, respectively, by default. We will use this measure to guide the geometric optimization of supporting parts in Section 4.

4. Designing Body-Supporting Assemblies

We present a computational approach for designing a body-supporting assembly for fitting a given body posture, i.e., determining the topology and geometry of the assembly modeled in Section 3. In particular, we focus on designing the supporting parts of the assembly since they determine comfortability; see Section 4.1. After that, we generate connecting parts to complete the assembly; see Section 4.2. Figure 5 shows an overview of our approach.

4.1. Designing Supporting Parts

The goal of designing supporting parts $\{P_i\}$ is to compute the number (K) of supporting parts, geometry and size of each supporting part P_i defined by the parameters $\{a_i, b_i, c_i, d_i\}$ and $\{\alpha_i, \beta_i\}$, respectively, and spatial placement of each supporting part P_i represented by a rotation R_i and a translation T_i. Solving all the parameters simultaneously is computationally intractable. Therefore, we present an approach that determines these parameters step by step.

Initializing supporting parts. We use the Skinned Multi-Person Linear (SMPL) model [LMR*15] to represent the human body with

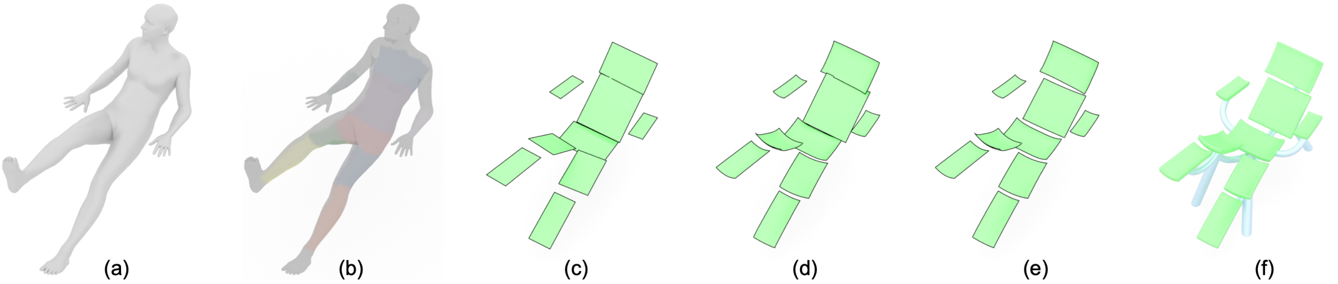


Figure 5: *Overview of our approach. Given (a) a human body posture as input, we first (b) identify the body regions that need supporting to (c) initialize the supporting parts. (d) The shape of each supporting part is then independently optimized to fit its corresponding body region. (e) Next, a global optimization is performed on the supporting parts to minimize the discomfort measure while preventing penetration and reducing material redundancy. (f) Lastly, connecting parts are generated to join the (thickened) supporting parts, collectively forming a complete body-supporting assembly.*

a given posture, which is a widely used parametric model of human body shape and pose. The SMPL model divides the human body into 24 semantic regions; see Figure 4 (left). In our approach, we did a post-processing on the body segmentation for designing body-supporting assemblies, resulting in 11 regions of the body that potentially need supporting; see Figure 4 (right). For each of the 11 regions, we compute the average pressure using the simplified force model [LBRM18] over its N downward-facing vertices $\{v_j\}$:

$$\bar{p} = \frac{1}{N}\sum_j p(v_j), \tag{6}$$

where v_j is a downward-facing vertex if $\mathbf{n}(v_j)\cdot\mathbf{g} > 0$, and $p(v_j)$ denotes the pressure evaluation at vertex v_j on the body region. We select body regions with $\bar{p}_i > 0.3$ as regions that need supporting denoted as $\{R_i\}$, each of which requires designing a corresponding supporting part; see Figure 5(b). Hence, the number of supporting parts, K, is the same as the number of body regions $\{R_i\}$ that need supporting. Note that users are allowed to adjust the threshold of $\bar{p}_i$ to control the number (K) of supporting parts. Moreover, they can interactively specify body regions that require support according to their preferences.

To initialize a supporting part P_i for each body region R_i, we first compute the oriented bounding box of the downward-facing vertices within R_i. Then, we select the most downward-facing face of the bounding box as the initial base surface S_i, represented by a planar quadrilateral; see Figure 5(c). The planar quadrilateral provides an initial spatial placement $\{R_i, T_i\}$ of the base surface S_i, along with the scale parameters $\{\alpha_i, \beta_i\}$ that define S_i's size. Each of the shape parameters $\{a_i, b_i, c_i, d_i\}$ is set as zero to model the geometry of the base surface S_i as a planar quadrilateral.

Local optimization of supporting parts. After the above step, we obtain an initial spatial placement and size for each supporting part. However, the shape of each supporting part's base surface is simply a planar quadrilateral, which cannot fit its corresponding body region well. To solve this problem, we perform a geometric optimization on each supporting part's base surface S_i independently. In detail, for each base surface S_i, we search for optimal shape parameters $\{a_i, b_i, c_i, d_i\}$ that minimize the discomfort measure $E^i_{\text{discomfort}}$ in Equation 5 while ensuring there is no intersection between the surface S_i and the human body; see Figure 5(d). Note that we keep the spatial placement $\{R_i, T_i\}$ and size $\{\alpha_i, \beta_i\}$ of the surface S_i fixed during the optimization.

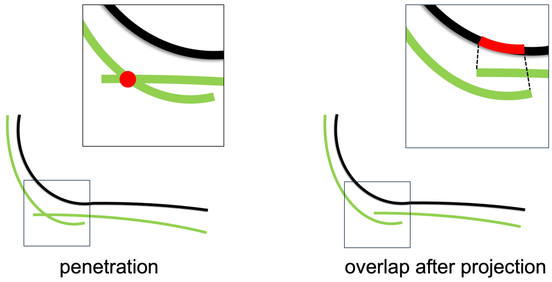


Figure 6: *After the local optimization of supporting parts, two undesirable cases may arise among supporting parts that are spatially close: (left) penetration, and (right) overlap between projections of two base surfaces onto the body surface.*

Global optimization of supporting parts. Despite the above local optimization, two undesirable cases may arise among supporting parts that are spatially close to one another: 1) penetrations (see Figure 6 (left)), which make the assembly not fabricable; and 2) overlaps between projections of base surfaces onto the body (see Figure 6 (right)), which do not contribute to the body supporting yet lead to unnecessary material usage. These two undesirable cases violates the Requirements 2 and 3 described in Section 3, respectively. Hence, we formulate two energy terms to resolve them.

Penetration energy. To prevent penetrations between a pair of supporting parts P_i and P_j, we define a penetration energy based on the minimum distance between their base surfaces S_i and S_j:

$$E^{ij}_{\text{penetration}} = \max\left(0, \epsilon - \min_{\mathbf{x}\in S_i, \mathbf{y}\in S_j} \|\mathbf{x}-\mathbf{y}\|\right)^2, \tag{7}$$

where $\mathbf{x}$ and $\mathbf{y}$ are the vertices on base surface S_i and S_j, respectively, and the constant ϵ defines the minimum clearance distance between any pair of base surfaces. In our experiments, ϵ is set equal to the default thickness (i.e., 5cm) of the supporting parts, aiming to avoid collisions among these parts.

Overlap energy. To eliminate overlaps between projections of base

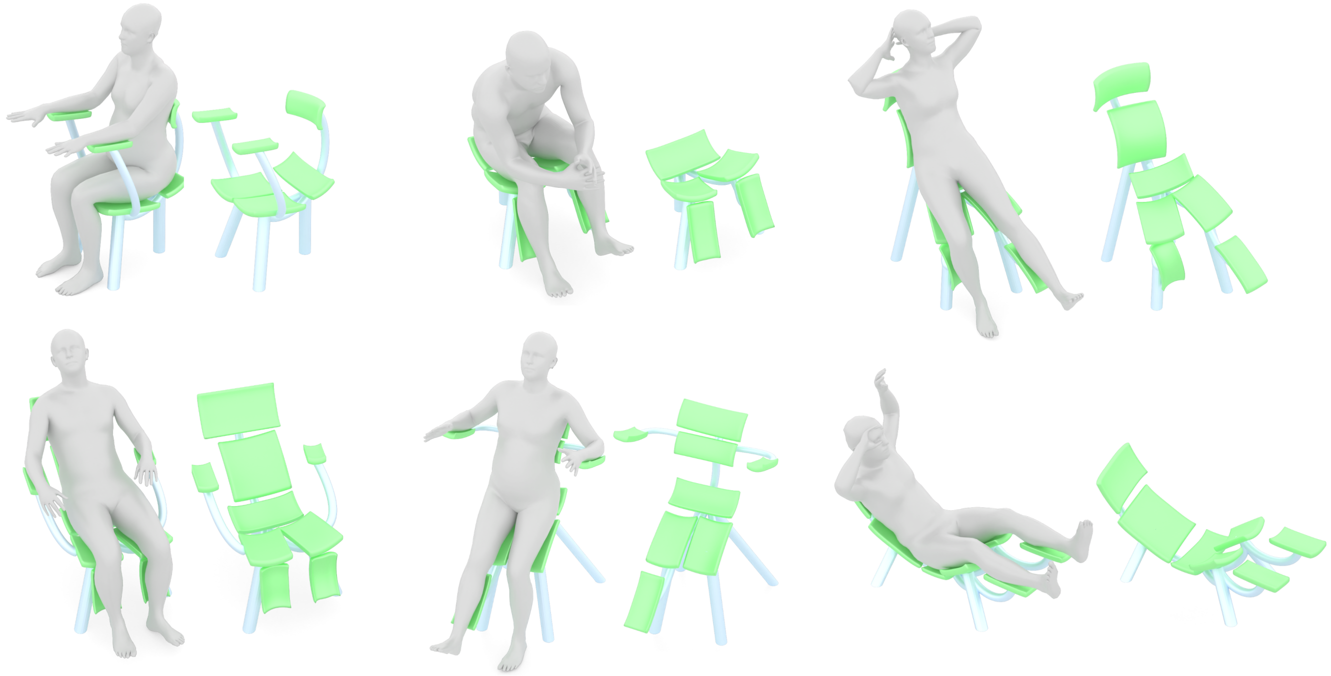


Figure 7: *Our approach allows designing body-supporting assemblies that fit a variety of body postures. For each result, we show the body-supporting assembly with and without the input body posture. The time taken to generate these results (from left to right, top to bottom) are 51.6, 46.2, 71.3, 62.5, 49.9, and 50.1 seconds, respectively.*

surfaces onto the body, we define an energy term for each pair of supporting parts with base surfaces S_i and S_j:

$$E^{ij}_{\text{overlap}} = A^{ij}_{\text{proj}}, \tag{8}$$

where A^{ij}_{proj} is the area of overlap between the projections of S_i and S_j onto the body surface.

We perform a global optimization on the geometry, size, and spatial placement of all the supporting parts; see Figure 5(e). The search space of this optimization problem is the set of parameters $\bigcup_{i=1}^{K}\{a_i, b_i, c_i, d_i, \alpha_i, \beta_i, R_i, T_i\}$ of all the supporting parts' base surfaces $\{S_i\}$. The goal of this optimization is to make the assembly comfortable to use while avoiding the penetration and overlap issues. Hence, we define the following objective to minimize:

$$E_{\text{global}} = \lambda_1 \sum_{i=1}^{K} E^{i}_{\text{discomfort}} + \lambda_2 \sum_{(i,j)\in\mathcal{N}} E^{ij}_{\text{penetration}} + \lambda_3 \sum_{(i,j)\in\mathcal{N}} E^{ij}_{\text{overlap}}, \tag{9}$$

where $\mathcal{N}$ denotes the set of supporting part pairs that are spatially close, and λ_1, λ_2, and λ_3 are weights set as 0.01, 1.0, and 1.0, respectively.

We solve both the local and global optimization problems using the Limited Memory Broyden-Fletcher-Goldfarb-Shanno Bound (L-BFGS-B) algorithm. In particular, the hard constraint of avoiding base surface-body intersection in Equation 3 is treated as a soft penalty term in the optimization. We obtain the geometry of each supporting part P_i by thickening the optimized based surface S_i and then rounding the edges using a loop subdivision algorithm.

4.2. Generating Connecting Parts

After designing the supporting parts, we generate connecting parts to complete the assembly using a procedural approach; see Figure 5(f). The procedural approach consists of the following steps:

1. *Generating connecting pillars.* We generate a connecting pillar for each supporting part that corresponds to some selected portions of the body, including back, thighs, and shanks. The geometry of each connecting pillar is modeled as a cylinder connecting the supporting part's center to the ground. By default, the cylinder radius is set to 3.0cm. The directions of the connecting pillars are determined to ensure that the resulting assembly is physically balanced. In detail, we determine the directions of the connecting pillars such that the support polygon of the assembly (i.e., the area enclosed by the contact points of the connecting pillars with the ground) is large enough to enclose the assembly's center of mass projected onto the ground.
2. *Generating connecting rods.* We generate a connecting rod for connecting a pair of supporting parts if their corresponding body regions are neighbors in the SMPL body model (e.g., lower back and upper back). One exception is that we allow generating a connecting rod for connecting a part supporting an arm to a part supporting a thigh or the back, as commonly practiced in furniture design discipline. The geometry of each connecting rod is modeled as a generalized cylinder (i.e., a thickened Bézier curve) that connects the centers of the associated supporting parts. By default, the radius of the generalized cylinder is set as 2.5cm. Note that if one of the supporting parts has a connect-

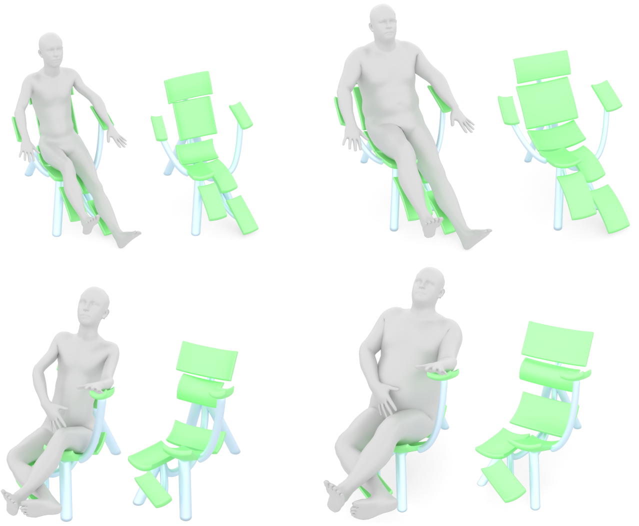


Figure 8: *Our approach allows designing body-supporting assemblies that adapt to different body shapes in the same posture: (left) slim and (right) broad body shapes. The time taken to generate these results (from left to right, top to bottom) are 51.6, 59.4, 52.4, and 56.8 seconds, respectively.*

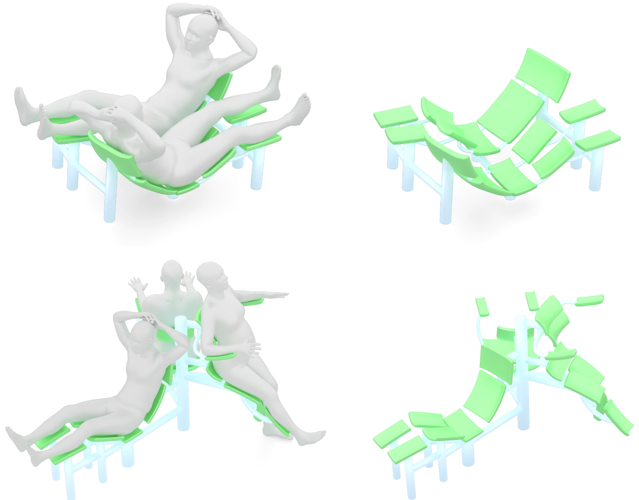


Figure 9: *Our approach can be extended to design multi-person body-supporting assemblies. The time taken to generate these two results are (top) 101.4 and (bottom) 153.6 seconds.*

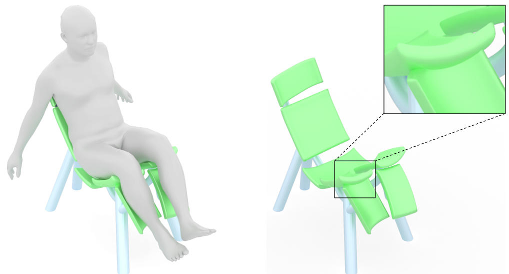


Figure 10: *A failure example in which two supporting parts collide with each other.*

ing pillar, we allow the connecting rod to connect to that pillar instead; see an example in Figure 1.

3. *Generating integral joints.* We use integral male and female joints to join the supporting parts and connecting parts, as commonly practiced in 3D printing [LBRM12]. In detail, we generate male joints at the two ends of each connecting rod, and the end of each connecting pillar that contacts a supporting part. We generate female joints on each supporting part at the location that contacts a connecting part. These integral joints not only make the assembly structurally stable, but also help to align the parts during the physical assembly process.

The output of our computational approach is a set of supporting parts and connecting parts that are ready for fabrication and assembly to form a usable body-supporting structure.

5. Results

Implementation. We implemented our computational design tool in Python on a desktop computer with a 3.7 GHz CPU and 16 GB memory. In particular, we use the `SciPy` library [VGO*20] to implement the L-BFGS-B optimization solver, which efficiently handles high-dimensional parameter spaces and bound constraints. We use the `NumPy` library [HMvdW*20] to implement some geometric computing operations such as point-to-surface distance and surface-to-surface distance. The entire local-global optimization typically takes around 60 seconds for a single input body posture.

Virtual results. Currently, we use two different methods to prepare input body postures: an interactive body model editor [Koc21] and a learning-based method for body reconstruction from a single photo [CPB*20]. Figure 7 shows that our computational tool allows designing personalized body-supporting assemblies for supporting a variety of input body postures, including office seating, forward-leaning, reclined, and lounging postures. In each result, our body-supporting assembly properly supports and fits different portions of the human body in a specific posture, including back, buttocks, legs, and arms. Figure 8 shows that our computational tool allows designing body-supporting assemblies that adapt to input bodies with different shapes (i.e., slim and broad shapes). For an input body with the same posture but different shapes, our tool designs body-supporting assemblies that have the same topology but different geometries since each supporting part's shape and size is optimized to fit a corresponding body region that needs supporting. Figure 9 shows that our approach can be extended to design body-supporting assemblies for multiple persons with specific postures. In detail, we first run our approach to design a body-supporting assembly for each individual person independently and then add additional connecting parts to combine these assemblies, forming a multi-person body-supporting assembly. Figure 10 shows an example failure case where two supporting parts collide with each other, making the assembly not fabricable. This failure happens since our global optimization treats the hard constraint of no penetration among supporting parts as a soft penalty term (i.e., the second term) in Equation 9. This issue can be resolved by increasing the weight λ_2 of the term in the global optimization.

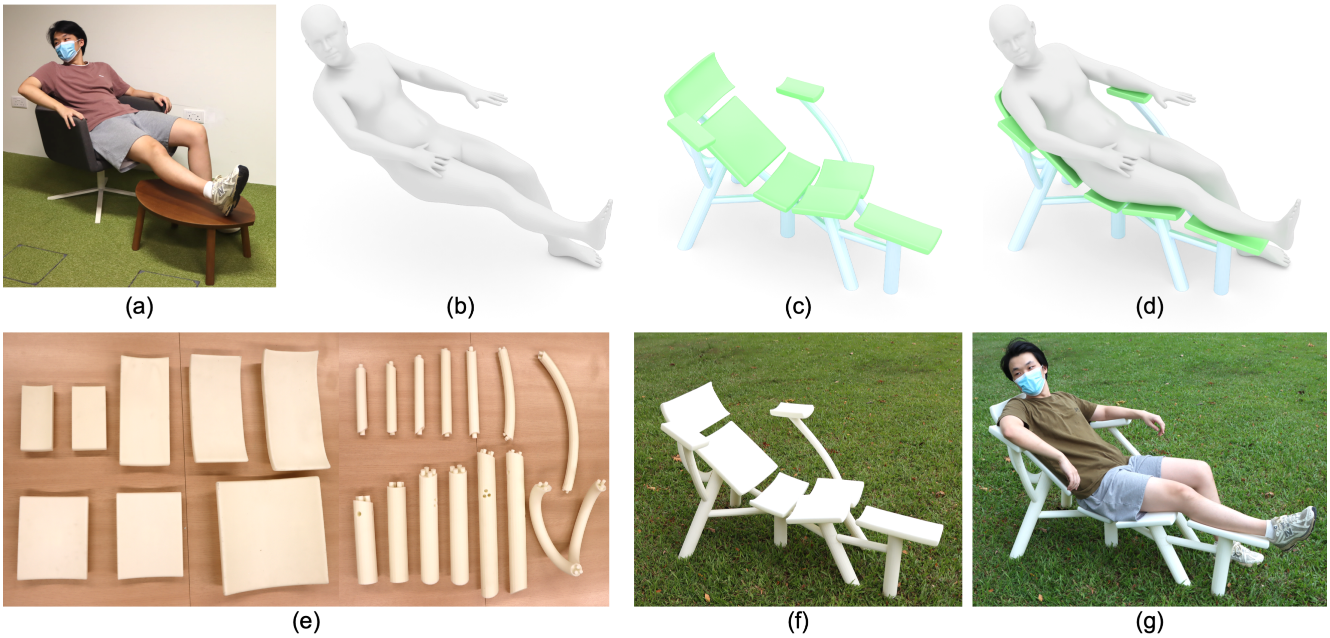


Figure 11: *Taking (a) a photo of a user in a preferred seating posture, (b) we reconstructed the user's body model and took it as the input of our design tool. (c&d) We designed a body-supporting assembly that fits the body posture using our tool, fabricated (e) the parts using 3D printing, and assembled them to form (f) a body-supporting assembly. (g) The user sits on the assembly to evaluate its usability.*

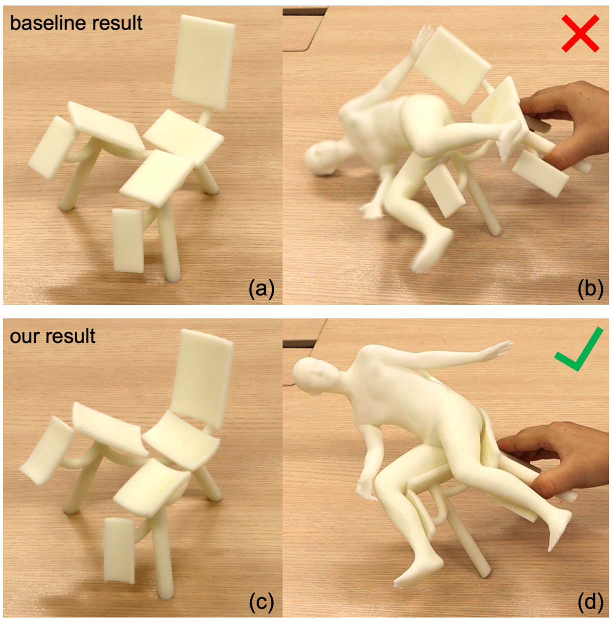


Figure 12: *We conducted a tilt analysis on (top) a baseline assembly and (bottom) our assembly, and showed that our assembly has a better performance in terms of preventing unintentional sliding of the human body.*

Physical prototype. As mentioned in Section 3, unintentional sliding off from a body-supporting shape makes people uncomfortable. We claim that supporting parts modeled as generalized hyperbolic paraboloids can fit different portions of bodies well and thus help to prevent the sliding issue. To validate this claim, we designed and fabricated two small-scale body-supporting assemblies for the same body posture. In detail, the baseline assembly is designed using a modified version of our approach that only optimizes the size and spatial placement but not the shapes of the supporting parts. Hence, each supporting part in the baseline assembly has a planar quadrilateral shape; see Figure 12(a). The other assembly is designed using our standard approach, resulting in curved shapes for the supporting parts; see Figure 12(c). We fabricated both assemblies as well as the input body using a SLA 3D printer with resin material. To validate that our assembly can better prevent the sliding issue than the baseline, we performed a tilt analysis on the two assemblies and measured the tilt angle at which the human body begins sliding off from each assembly. Figure 12(b) shows that the human body began sliding off from the baseline assembly at the tilt angle of around 45°. However, at the same tilt angle, the human body remained steady on our assembly, confirming its better performance in preventing unintentional sliding; see Figure 12(d). Please watch the accompanying video for a live demo.

Informal user study. We conducted an informal user study to evaluate the usability of our designed body-supporting assembly. To this end, we recruited one participant (male, 25 years old) for the study. We first took a photo of the user in a preferred seating posture and then reconstructed the user's body model using a learning-based approach [CPB*20]; see Figure 11(a&b). Next, we used our computational tool to design a body-supporting assembly that fits the body posture; see Figure 11(c&d). We fabricated the parts using a SLA 3D printer with resin material and assembled them manually to form a body-supporting assembly; see Figure 11(e&f).

During the user study, we asked the user to sit on the assembly with the preferred posture for 20 minutes, during which the user was allowed to perform slight body movements freely; see Figure 11(g). As a baseline, the user also sat on a standard chair with the preferred posture for the same duration; see Figure 11(a). The user reported that our body-supporting assembly provides a more comfortable seating experience than the baseline, particularly in large body regions such as the lower back, thighs, and shoulders. The user also reported a feeling of smaller body pressure and less unintentional sliding during prolonged sitting, thanks to the optimized shapes of our supporting parts. Overall, the user prefers to use our body-supporting assembly for sitting. These feedbacks validate that our designed body-supporting assembly is not only usable in practice but also able to ergonomically support a user in his/her preferred body posture. Please watch the accompanying video for demos.

6. Conclusion

The paper presents a computational approach for designing a body-supporting assembly that fits a human body with a given posture, aiming to make the assembly comfortable to use for that person. We propose a family of computational techniques to model, evaluate, and design a personalized body-supporting assembly, and integrate these techniques into a computational tool that greatly simplifies the design process. We have employed our computational tool to design personalized body-supporting assemblies for human bodies with a variety of postures and shapes, and fabricated two of them for physical validation. Our user study on a full-scale body-supporting assembly designed by our approach confirms that our assembly is more comfortable to seat than a standard chair.

Limitations and future work. Our work has several limitations that open up promising directions for future research. First, our discomfort measure assumes that the human body is rigid to simplify the computation. In the future, we plan to improve our discomfort measure by modeling the human body as a deformable shape and simulating the body-supporting process using FEM similar to [ZLC*22]. Second, our approach assumes a fixed body posture as the design input. However, some person may have more than one preferred postures during sitting. One interesting future work is to extend our current approach to support multiple postures for a single person. Third, our approach uses male and female joints to join the supporting parts and connecting parts. In the future, we plan to enhance structural stability of the resulting assembly by planing different types of joints using an interlocking method [Son22]. Lastly, our current approach assumes the supporting parts are rigid and focuses on geometric design and optimization, making them useful for designing supporting parts made from hard materials such as wood and steel. In the future, we plan to investigate the modeling and design of supporting parts that are deformable such as those made from foam and rubber, which requires joint optimization of the geometry and materials.

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