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# Scanning and Animating Characters Dressed in Multiple-layer Garments

Pengpeng Hu · Taku Komura · Daniel Holden · Yueqi Zhong



**Fig.1** Snapshots of a character model fully-dressed in multiple-layers of garments. The multi-layer garment model is synthesized from 3D scan data, and a motion capture data is imported to control the character. The animated garment is a result of blending the motions computed by physically-based animation and linear blend skinning.

**Abstract** Despite the development of user-friendly interfaces for modeling garments and putting them onto characters, preparing a character dressed in multiple layers of garments can be very time-consuming and tedious. In this paper, we propose a novel scanning-based solution for modelling and animating characters wearing multiple layers of clothes. This is achieved by making use of real clothes and human bodies. We first scan the naked body of a subject by an RGBD camera, and a statistical body model is fit to the scanned data. This results in a skinned articulated model of the subject. The subject is then asked to put on one piece of garment after another, and the articulated body model dressed up to the previous step is fit to the newly scanned data. The new garment is segmented in a semi-automatic fashion and added as an additional layer to the multi-layer garment model. During runtime, the skinned character is controlled based on the motion capture data and the multi-layer garment model is controlled by blending the movements computed by physical simulation and linear blend skinning, such that the cloth preserves its shape while it shows realistic physical motion. We present results where the character is wearing multiple layers of garments including a shirt, coat and a skirt. Our framework can be useful for preparing and animating dressed characters for computer games and films.

**Keywords** Cloth animation, 3D scanning

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## 1 Introduction

There is a rising demand for realistic dressed characters in films and computer games. Due to the rising computational power and the development of cloth simulation techniques [Sofien et al. 2014; Wang et al. 2015; Tang et al. 2016], garments of thousands of vertices can be animated by physical simulation in real-time. The realistic movements of clothes can greatly attract the audience of films and the game players.

Despite such progress on the simulation side there is a bottleneck on the modelling side. Currently, such garment models need to be designed by the animators, which can be very time-consuming when the right template is not prepared in advance. Another issue is to putting such clothes onto the characters, which can be extremely tedious and time-consuming despite the development of easy-to-use user interfaces [Nobuyuki et al. 2011, Igarashi and Hughes 2006].

Another bottleneck is the multi-layer configuration of garments. As characters usually wear clothes on top of another, animating them in a realistic fashion is important for improving the impression of the audience. On the contrary, preparing such configurations can be again extremely time-consuming as the dressing process needs to be repeated many times. Also, the simulation process will become very slow due to the intense contacts and collisions.

In this paper, we propose a novel scanning-based solution for modelling and animating characters dressed in multiple layers of clothes. We make use of real human bodies and clothes for this purpose. We first scan the naked body by an RGBD camera, and a statistical body model is fit to the scanned data. This results in a skinned articulated model of the subject. The subject is then asked to put on one piece of garment after another, and the body model dressed up to the previous step is fit to the newly scanned data. The new dress is segmented out in a semi-automatic fashion and added as a layer to the multi-layer garment model.

During runtime, using the character dressed in multiple layers of clothes, we can realistically animate the clothes by blending the deformation of the clothes by linear blend skinning and physical simulation. This approach is beneficial as the shape of the cloth can be preserved in a natural fashion while physical movements of the skirt and the coat can be simulated.

Our pipeline can be useful for preparing dressed characters such as those for computer games and films. To our best knowledge, this is the first paper to animate multiple-layer cloth based on 3D scan.

Our main contributions are:

- A novel framework to reconstruct multiple-layer garments from 3D scanned data.
- A method to create new plausible multiple-layer cloth animation by blending physically-based and linear blending skinning.

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## 2 Related Work

In this section, we first review techniques for scanning the 3D static body, and next about performance capture techniques, which scan and track the dynamic movements of the subjects. Then, we discuss techniques to animate dressed 3D characters, and finally about graphical user interfaces for dressing characters.

### 2.1 3D Body Scanning

Acquiring 3D geometric models from real world objects is a topic that has been extensively explored, amongst which the 3D shape reconstruction of human subjects is of specific interests in computer graphics and apparel design. Scanning devices based on structured light [Rocchini et al. 2001] or laser scanners [Istook et al. 2001] can capture the human body in high resolution. Although such devices used to be expensive, consumer-level depth cameras are becoming widely amiable. The Kinect camera [Zhang 2012; Han et al. 2013] is one of such depth cameras that is recently used for full-body scans. For example, the work by Tong et al. [2012] uses three Kinect devices and a turntable to scan the body from all directions. The work by Zeng et al. [2013] uses two Kinect cameras in the form of the self-turning subject. More work has been done by only one Kinect sensor [Izadi et al. 2011; Cui et al. 2012]. To rapidly scan the human body, multiple depth cameras are fixed from various views, and the 3D model is obtained by calibrating these fixed depth cameras to align the data precisely [Alexiadis et al. 2013]. All these works capture the static geometry of human subjects. They can be rigged

to skeletons to be animated as virtual character [Baran et al. 2007, Feng et al. 2015]. This topic is further covered in Section 2.3.

The bodies reconstructed by these methods only have the outmost surface. We focus on reconstructing a multiple-layer garment model, which can later be animated.

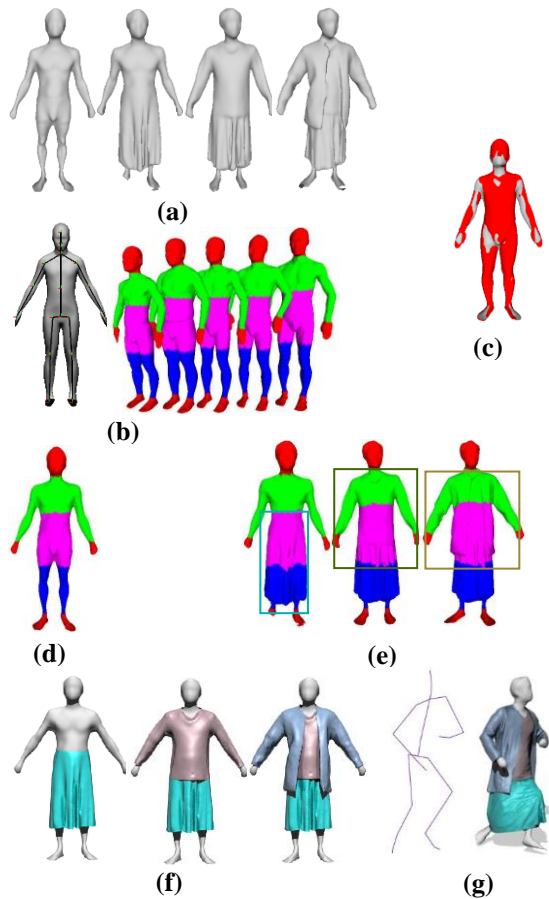
### 2.2 Animating Characters by Performance Capture

Performance capture is a technique to scan and track the dynamic movements of subjects usually by multi-view stereo. It enables the reconstruction of detailed motion and time-varying geometry of humans. Wu et al. [2013] track the surface of the subjects using multiple cameras and fit template models to them. One issue with the performance capture is in the limited resolution, thus fail to detect fast, high-resolution movements. Vlasic et al. [2009] use a large setup with 120 light sources and 8 cameras to obtain high resolution and merge the surfaces captured from different directions. Stoll et al. [2010] fit a statistical model to the dressed body and detect the wavy cloth regions, and then improve the animation of such areas using physical simulation. The setup for performance capture is rather expensive, and a specialized environment is usually needed. Therefore we propose a setup to extract garments from static scans and apply physical simulation to animate the garments.

### 2.3 Animating Dressed Virtual Humans

Dressed virtual humans became abundant in 3D games, virtual reality applications, and movies. A simple way to animate clothes is to apply linear blend skinning. The work by Oh et al. [2005] presents a technique for computing the skinning weights for the cloth vertices. They show the method is applicable even for clothes like skirts, where the topology is very different from the body shape. Xu et al. [2014] propose a data-driven approach where the blending weights are learned from the example poses. Such an approach can deform the cloth in a more realistic fashion for a wide range of poses. Unfortunately, linear blend skinning has issues animating highly dynamic clothes. For the case of skirts, the results will appear non-plausible when there is large deformation due to the wind or acceleration/deceleration.

Another topic that has been explored in the animation community is garment transfer. In works proposed by [Cordier et al. 2002, Cordier et al. 2003], the garments worn on a 3D body model are automatically resized according to the geometry of the body size. They first attach the cloth mesh to the body surface by defining attachment area between the garment mesh and the skin surface. Brouet et al. [2012] similarly transfer dresses to

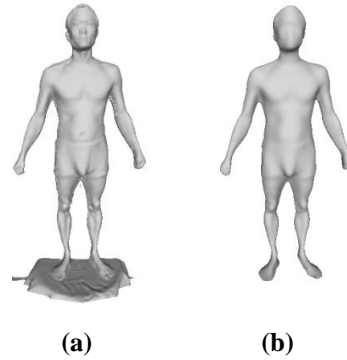


**Fig.2 Overview of our method: (a) scanning a subject in an iterative manner; (b) a rigged template and the pre-labeled statistic body database; (c) approximating the naked body using a morphable template; (d) rigging and segmenting the naked body via correspondences automatically; (e) automatically extracting rough cloth from dressed bodies via transferring segmentation (f) dressing the naked body; (g) combination of physically-based simulation and linear blending skinning.**

different characters by making use of the spatial relations of the body and the clothes in the template model. These approaches require preparing the templates, and for that the clothes have to be put on the human characters in the first place. The problem that we solve in this paper is to improve the pipeline for preparing such a dressed model.

#### 2.4 Graphical User Interfaces for Dressing Characters

Another direction of research that is being sought is improving the graphical user interfaces for designing clothes and dressing characters. Igarashi and Hughes [2006] propose an intuitive interface where they draw sketch lines over the dress and the body that should overlap when the dress is worn. Umetani et al. [2011] propose a bidirectional interface that maps the worn dresses and its unfolded 2D patterns. Although these interfaces can significantly reduce the cost of the animators, using such GUIs is still a time-consuming process.



**(a) KinectFusion data (b) mesh processed model**  
**Fig.3 3D scan result**

### 3 Overview

Our goal is to animate characters with fully-dressed multiple-layer garments created from body scans. We start by capturing the naked and dressed bodies (see Section 4). Then, a statistical human body model based on the Japanese body database is used to automatically produce a rigged body model of the subject, in a way similar to the work of [Feng et al. 2015] (see Section 5). Next we segment the clothes from the scans and construct a multi-layer garment model worn by the subject character. This is done by applying constrained articulated-ICP to fit the body model with one less dress to the next scan, such that the body model is under the skin of the scan (see Section 6.1). Once aligned, the geometry of the next dress is segmented in a semi-automatic manner (see Section 6.2, 3), and added as an additional layer of garment to the dressed model. During runtime, the physically animated cloth and the configuration by linear blend skinning are blended together to generate plausible cloth movements (see Section 7).

### 4 Scanning the Body

We scan and capture the body surface of a subject by Kinect Fusion [Izadi et al. 2011]. The subject stands on a turn table in an A-pose and the body is rotated in front of the camera for 30 seconds. Kinect V2 is chosen in our work as it has a higher depth resolution. Once the data is captured, it is decimated, de-noised, and smoothed to reduce the cost of the following procedures (see Fig 3).

Starting from the naked body, the subject is asked to put on one garment at a time and each time the body is scanned as described above (see Fig 2.a). These scanned models are further analyzed to reconstruct a dressed character with multiple-layers of garments. More details are explained in the following sections.

## 5 Automatic Rigging

In this section, we describe the process to fit a statistical body model into the scanned naked body and rigging it with a skeleton model. We apply the Japanese statistical body model developed from the AIST/HQL Anthropometric Database by Yamazaki et al. [2013].

### 5.1 Construction of the Statistical Body Model

A morphable human model is constructed from the Japanese body database [Yamazaki et al. 2013]; using a rigged template mesh and a set of 3D human models in different sizes in A-pose, we define a PCA-based statistical body model.

The template mesh is defined by  $X = \{V, T, J\}$  where  $V = \{v_1, \dots, v_{|V|}\}$  are the vertices,  $T = \{t_1, \dots, t_{|T|}\}$  are the triangles and  $J = \{j_1, \dots, j_{|J|}\}$  are the joints of the body. A set of skin weights  $w(v_i) = \{w^1(v_i), \dots, w^{|J|}(v_i)\}$  are defined for each vertex  $v_i$  in  $X$  which are used for linear blend skinning for changing the pose of the template mesh. The joint centers are also predicted manually by inserting a skeleton using existing modelling software. This needs to be done only once for the template model.

The template mesh is fit to the point cloud data of different body scans by non-rigid registration [Yamazaki et al. 2013]. As a result, different body models with the same mesh topology can be obtained, which we can use for building the statistical body model. During this process, we can also transfer parameters such as the joint centers and the skin weights. For the joint centers, they are transferred using mean value coordinates (MVC) [Ju et al. 2005]. The assumption is that the MVC of the joint positions are consistent among different body models in the database in A-pose. Using the MVC of each joint  $j_n, n = 1 \dots |J|$  in the rigged template mesh, the joint position can be computed by

$$j_n = \sum_i m^n(v_i) v_i \quad (1)$$

where  $m^n(v_i)$  is the mean-value coordinates of  $j_n$  for joint  $v_i$ . Thus as the shape parameters change, we can use vertex positions  $v_i'$  from the newly reconstructed body shape  $V'$  to infer the new joint locations. Examples of applying this approach for predicting the joint positions of different character models are shown in Fig. 4. We can use the same skin weights from the template mesh after the fitting, as the topology of the mesh remains the same.

Finally, a statistical PCA body model  $S_k(\beta)$  is constructed:

$$S_k(\beta) = \text{mean} + \sum_{i=1}^k \beta^i \mu^i, \quad (2)$$

where  $\beta^i$  is the coefficient of the PCA basis  $\mu^i$  computed from the Japanese body database, and  $k = 15$  in our experiments. Using this model, arbitrary body shapes can be constructed by adjusting the coefficients  $\beta$  (see Fig. 5). Ahead of computing the statistical body model, the poses of each body model are slightly adjusted using linear blend skinning, such that the joint angles are all the same for each body model.

### 5.2 Fitting the Statistical Body Model to the Body Scans

We now fit the statistical body model to the newly scanned subject using the method described in Section 4, by simultaneously predicting the low dimensional body parameters  $\beta$  and the joint angles  $\theta$ . Using linear blend skinning, we can now deform the shape of the morphable body model by changing the joint angles  $\theta$ :

$$D(\theta, v_i) = \sum_j w^j(v_i) R_j(\theta) v_i \quad (3)$$

where  $R_j(\theta)$  is the global bone transformation of joint  $j_i$  computed using the skeletal hierarchy and the joint angles  $\theta$ . As  $v_i$  is a function of  $\beta$  of the statistical body model (see Eq.2), we can define a morphable body model  $M(\theta, \beta)$  to denote a morphable model that represents the 3D human geometry of different body shapes in different poses.

Finally, we fit the model  $M(\theta, \beta)$  to the scanned naked body  $Y$ . The fitting is done by optimizing  $\theta$  and  $\beta$  such that  $M$  becomes an approximation for  $Y$ . The following optimization problem is solved for this purpose:

$$\arg \min_{\theta, \beta} \sum \|M(\theta, \beta) - Y\|. \quad (4)$$

As the topology of the newly scanned body is not the same as the template model, we need to compute the blending weights for its vertices. To compute the skin blending weights  $w(z_i)$  for the scanned naked body, we project each vertex  $z_i$  onto the closest triangle of  $M$  and use barycentric coordinates to interpolate the skin weights. Hence, the scanned naked body can be automatically rigged.

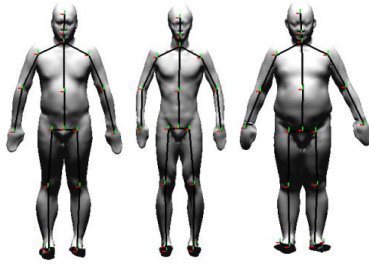


Fig. 4 Japanese body models with the corresponding morphable skeletons fitted.

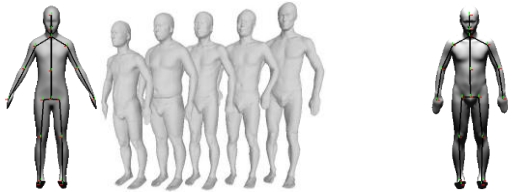


Fig.5 3D morphable human models (left) and the mean model (right).

## 6. Reconstructing a Multiple-layer Garment Model

The procedure to construct a multi-layer garment model can be divided into the following three steps: fitting the character model to the scanned body with one more dress (see Section 6.1), extracting the additional dress from the scanned data (see Section 6.2) and overlapping the extracted cloth model with one another to construct the multilayer cloth model (see Section 6.3).

There are two main challenges here:

- Making sure that the body is within the dress and it does not penetrate the clothes, despite non-rigid deformations of the clothes as well as the body (breathing slightly deforms the torso).
- The hem of extracted cloth from dressed body should be complete and smooth.

We also describe how we cope with these issues in the rest of this section.

### 6.1 Fitting a Naked Body under a Dressed Model

Articulated-ICP [Tagliasacchi et al. 2015] is used to change the pose of a source articulated mesh to the pose of a target articulated mesh. As the character model is rigged with the skeleton, we can optimize its posture to fit the scanned data, by solving the following problem:

$$\arg \min_{\theta} \sum \|N(\theta) - M_p\|^2 \quad (5)$$

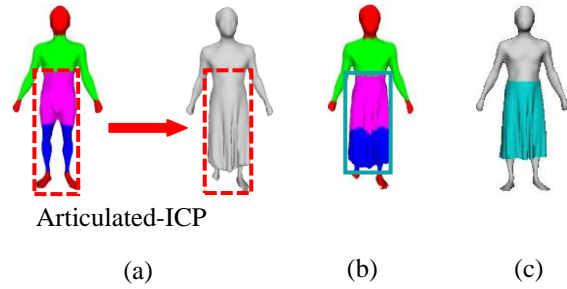


Fig.6 (a) Fitting legs of the naked body inside the skirt; (b) Automatically extracting the rough skirt; Segmenting the skirt into two parts to calculate blending weights for cloth animation (c) dressing the skirt on the naked body.

where  $N(\theta)$  denotes the body model with one less dress and  $\theta$  is the concatenation of the chosen joint angles in the skeleton and  $M_p$  is the dressed body. Simply optimizing Eq. 5 may not suffice our requirements as there is a chance that the character's body may penetrate the scanned model.

As we are assuming that the scanned body is wearing more clothes than the character model, we add an additional constraint for keeping the body model inside the dressed scan. Thus we solve the same problem with an additional constraint as below:

$$\arg \min_{\theta} \sum \|N(\theta) - M_p\|^2 \quad (6)$$

$$\text{s.t. } (N_{\text{correspondence}(i)}(M_p) - N_i) \bullet n_i > 0$$

where  $N_i$  represents the vertex coordinate of selected part of naked body,  $N_{\text{correspondence}(i)}(M_p)$  denotes the correspondence of  $N_i$  in  $M_p$ , and  $n_i$  is the normal of  $N_i$ .

### 6.2 Cloth Extraction

To extract a precise scanned garment from a dressed body, we propose a semi-automatic method, starting by automatically extracting the rough garment and then manually selecting the smooth hem. It can work well for extracting both tight and loose garments.

For the initial rough segmentation, we prepare a number of rough segmentations of the body model for each dress types as shown in Fig.6. The user first selects the segmentation template according to the dress that is to be segmented. Once the body model is fit to the scanned surface, the vertices of the scanned surfaces are labeled according to the nearest vertex of the body model.

As shown in Fig.6 (b), the segmentation can be transferred from body model to the skirt body. A rough skirt can be automatically extracted via our body segmentation method.

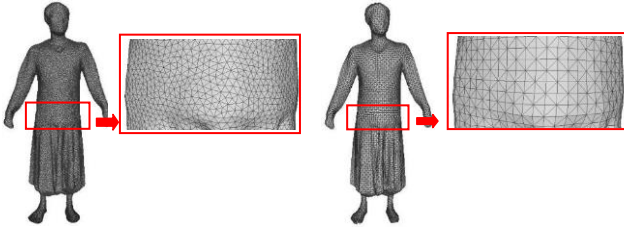


Fig.7 original triangle mesh (b)quad mesh

This segmentation is then manually fixed by using a painting interface. To make the mesh edit easier for the user, we remesh the dressed body to a quad mesh structure using the method proposed by [Jakob et al. 2015] (see Fig.7). This enables the extraction of a smooth boundary for the skirt from the scanned model. It costs about 90 seconds to manually cut along the boundary of the clothes.

### 6.3 Layering Garments

The clothes extracted by the segmentation process are overlaid and a multi-cloth model is constructed. Due to the non-rigid deformation of the clothes and the body, penetration between the body and the clothes or between the clothes can occur despite solving Eq. 5. Hence, we resolve this penetration issue by pushing the vertex along its normal direction:

$$v' = v + (k + d) \times \text{norm}(v) \quad (7)$$

where  $v$  is the position of the point in the cloth which is inside the naked body,  $\text{norm}(v)$  is the normal of  $v$ ,  $d$  denotes the distance between  $v$  and its closest point in the naked body,  $k$  is a coefficient, and  $v'$  is the updated position of  $v$ . Although more advanced methods for resolving complex penetration issues, such as those by [Zhang et al. 2015] exists, we find our simple approach good enough for our purpose due to the minority of the non-rigid deformation occurring here. Fig.2 (f) shows the final multiple cloth model dressed in a character.

## 7. Animating Dressed Characters

### 7.1 Blending Physically-based and Skinned Animation

When animating the movements of the clothes, we blend the motions computed by physically based animation and linear blend skinning for the following reasons. Although physically based animation can produce realistic particle movements, it suffers from the effect of dropping down, making it less puffy and volumetric as they were during the

original scan. More accurate elasticity and stiffness values might help, but it is difficult to predict such parameters. Also, there is an effect of air between the clothes and the body, whose computation require fluid simulation. Taking into account such effects will significantly increase the computational cost as well as memory consumption. On the contrary, linear blend skinning can preserve the shape of the clothes but makes it appear too rigid and unnatural especially for dresses like skirts.

Our solution is to blend the physically-based simulation and linear blending skinning to obtain high-quality animation of dressed characters. The process is as follows:

- Transfer the skin weights from the naked body to each layer of cloth model,
- control the skeleton by importing motion capture data,
- set the appropriate cloth simulation parameters for each layer of clothes, and
- blend the animation by physically-based simulation and linear blend skinning using the following equation:

$$Mesh_{blend} = w_p \times Mesh_{physical} + w_{lbs} \times Mesh_{LBS}, \quad (8)$$

where  $w_p$  and  $w_{lbs}$  are the blending weights of the physical simulation and linear blend skinning, such that  $w_p + w_{lbs} = 1$ .

We propose a method to automatically calculate the blending weights for Eq.8. We firstly find the closest points on the naked body for all the points of the garment and calculate the distances between such pairs. The maximum, minimum and the mean of such distances are denoted by  $dist_{max}$ ,  $dist_{min}$ , and  $dist_{mean}$ , respectively. Then the physical weight  $w_p$  in Eq.8 is calculated by the following equation:

$$w_p = \begin{cases} \frac{(dist_{mean} - dist_{min})}{(dist_{max} - dist_{min})} & \text{if } \frac{(dist_{mean} - dist_{min})}{(dist_{max} - dist_{min})} < 0.5. \\ 0.5 & \text{otherwise} \end{cases} \quad (9)$$

We have a special treatment for the skirt, as the top of the skirt is much closer to the naked body where the bottom part is further away. Thus the skirt is segmented into two parts during the segmentation and the blending weights for them are calculated separately.

## 8. Experimental Results

We tested our pipeline with shirts, pants, skirts and coats. In our first example, we show results where the character is dressed in summer style, with a pants and shirt (see Fig. 8 (a)), and a one piece with a skirt (see Fig. 8(b)). The clothes deform in a way that preserves the original shape while following the laws of physics; for example, the pants in Fig 8.(a) keeps its distance from the thighs while deforming according to the leg swing. For the one piece, the skirt will drip and deform when it contacts the body.

Next, we show an example where the character is dressed in five layers (see Fig. 9,10). Dressing a character in many layers of garments can be very time consuming with previous approaches. Our pipeline can easily achieve this by simply scanning the body many times (see Fig. 9). The dressed body appears much puffier than simply wearing single layers of clothes.

Finally, we show and compare results when the garments are deformed by linear blend skinning (see Fig. 11(a)), physically-based animation (see Fig. 11(b)) and our approach (see Fig. 11(c)). When the deformation is computed by linear blend skinning, the skirt deforms rigidly, resulting in the skirt splitting in the middle when the character walks. When physically-based animation is applied for the same motion, the coat of the character drops off from the shoulder, resulting in an undesired effect. Finally, when our approach is used, the coat is kept worn and the skirt deforms naturally. Table 1 illustrates the time required for computing one frame on a laptop (Intel(R) Core(TM)i-54210 M CPU @ 2.60GHz 4GB RAM). The computation of the physical simulation is done using Maya's *nCloth*.



(a) Snapshots of an animation of a character wearing a T-shirt and shorts, and



(b) snapshots of a character dressed in one piece.

Fig.8 Animation for the character dressed summer clothes

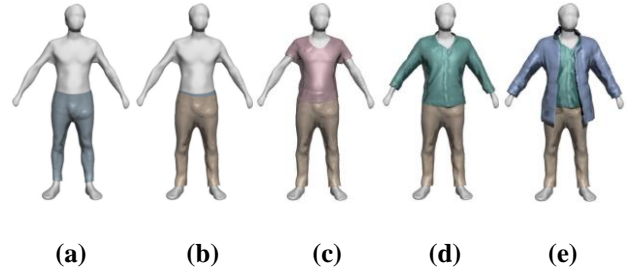
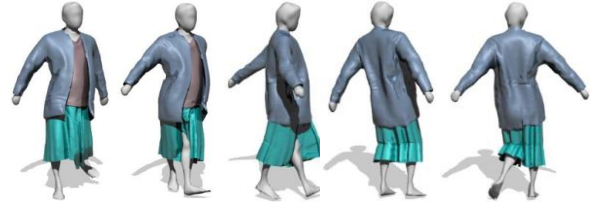


Fig.9 5-layer cloth model: (a) first layer; (b) second layer; (c) third layer; (d) fourth layer; (e) fifth layer;



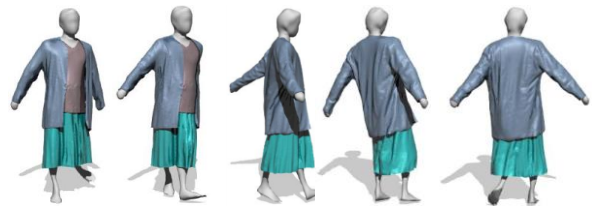
Fig.10 Animation of a character dressed in 5 layers of garments.



(a) Results by linear blend skinning.



(b) results by physically-based simulation, and



(c) the results by our method, where the motion by linear blend skinning and physical simulation are blended.

Fig.11 Comparison of animation by three different approaches.

LBS	0.2s
Physical Simulation	0.48s
Our method	0.5s

Table 1. Computation time per frame by different approaches



## 9. Discussion and Conclusion

We present a novel scanning-based pipeline for animating characters dressed in multiple layers of cloth. To the best of our knowledge, this is the first paper to animate multiple-layers of garments captured by 3D scanners. Multi-layer garment models can be reconstructed in an iterative manner. Combination of physically-based simulation and linear blending skinning is used for plausible cloth animation. The blending weights can be automatically calculated from the average closest distances between the body vertices and the cloth vertices.

Compared to previous methods, our system has the following advantages:

- Only simple and intuitive user intervention is needed for composing a complex multi-layer garment model.
- The system only requires static body scans.
- The shape of the original cloth can be preserved while animating physical effects of loose garments such as the skirt.

Our method also has some limitations. The segmentation of the clothes requires human manual adjustment, although this process is very simple when using the 3D painting interface. We hope to extend our work to the scanned body with arbitrary poses, and make the clothes extraction fully automatic in the future.

Currently, the physical parameters of the clothes such as the elasticity and the stiffness are set manually by the user. It will be useful to estimate such parameters automatically from the scans. Such a computation will also be fruitful for the apparel/textile industry.

Finally, there is an increasing interest in simulating the process to put on clothes [Ho and Komura 2009, Wang et al. 2013, Clegg et al. 2015]. Simulating the process of dressing different types of clothes on top of another can be an interesting research direction in the future.

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## References

1. Alexiadis D S, Zarpalas D, Daras P. Real-time, full 3-D reconstruction of moving foreground objects from multiple consumer depth cameras. *IEEE Transactions on Multimedia*, 15(2): 339-358,2013.
2. Baran, Ilya, and Jovan Popović. "Automatic rigging and animation of 3d characters.", *ACM Transactions on Graphics*, Vol. 26. No. 3. ACM,2007.
3. Clegg A, Tan J, Turk G, Liu CK, Animating Human Dressing, *ACM Transactions on Graphics*, vol. 34, no. 4,2015.
4. Cordier F, Magnena-Thalmann N., Real-time animation of dressed virtual humans, *Computer Graphics Forum*, 21(3): 327-335,2002.
5. Cordier F, Seo H, Magnenat-Thalmann N. Made-to-measure technologies for an online clothing store, *IEEE Computer graphics and applications*, 23(1): 38-48,2003.
6. Cui Y, Chang W, Nöll T, et al. KinectAvatar: fully automatic body capture using a single Kinect, *Asian Conference on Computer Vision*, : 133-147,2012.
7. Feng A, Casas D, Shapiro A. Avatar reshaping and automatic rigging using a deformable model, *Proceedings of the 8th ACM SIGGRAPH Conference on Motion in Games*, : 57-64,2015.
8. Han, J., Shao, L., Xu, D., & Shotton, J. Enhanced computer vision with microsoft kinect sensor: A review. *IEEE Transactions on Cybernetics*, 43(5), 1318-1334,2013.
9. Ho ESL, Komura T, Character Motion Synthesis by Topology Coordinates, *Computer Graphics Forum* 28(2), 299-308 ,2009.
10. Wang H. A chebyshev semi-iterative approach for accelerating projective and position-based dynamics[J]. *ACM Transactions on Graphics (TOG)*, 34(6): 246,2015.
11. Istook C L, Hwang S J. 3D body scanning systems with application to the apparel industry. *Journal of Fashion Marketing and Management: An International Journal*, 5(2): 120-132,2001.
12. Igarashi, Takeo, and John F. Hughes. "Clothing manipulation." *ACM SIGGRAPH 2006 Courses*,2006.
13. Izadi S, Kim D, Hilliges O, et al. KinectFusion: real-time 3D reconstruction and interaction using a moving depth camera, *Proceedings of the 24th annual ACM Symposium on User Interface Software and Technology*. : 559-568,2011.
14. Ju T, Schaefer S, Warren J. Mean value coordinates for closed triangular meshes, *ACM Transactions on Graphics*, 24(3): 561-566,2005.
15. Jakob W, Tarini M, Panozzo D, et al. Instant field-aligned meshes, *ACM Transactions on Graphics*, 34(6): 15,2015.
16. Tang M, Wang H, Tang L, Tong R, Manocha D. CAMA: Contact-aware matrix assembly with unified collision handling for GPU-based cloth simulation.

- Computer Graphics Forum, 35(2),2016.
17. Umetani N, Kaufman DM, Igarashi T et al., Sensitive Couture for Interactive Garment Editing and Modeling, ACM Transactions on Graphics (SIGGRAPH 2011), 30(4),2011.
  18. Oh S, Kim H, Magnenat-Thalmann N, et al. Generating unified model for dressed virtual humans. The Visual Computer, 21(8): 522-531,2005.
  19. Rocchini C, Cignoni P, Montani C, et al. A low cost 3 D scanner based on structured light. Computer Graphics Forum. 20(3): 299-308,2001.
  20. Rémi Brouet, Alla Sheffer, Laurence Boissieux, Marie-Paule Cani. Design Preserving Garment Transfer. ACM Transactions on Graphics, 31 (4),2012.
  21. Stoll C, Gall J, De Aguiar E, et al. Video-based reconstruction of animatable human characters. ACM Transactions on Graphics, 29(6),2010.
  22. Bouaziz S, Martin S, Liu T, Kavan L, Pauly M. Projective Dynamics: Fusing Constraint Projections for Fast Simulation. ACM Transaction on Graphics 33(4)(2014)
  23. Tong J, Zhou J, Liu L, et al. Scanning 3d full human bodies using kinects. IEEE Transactions on Visualization and Computer Graphics, 18(4): 643-650,2012.
  24. Tagliasacchi A, Schröder M, Tkach A, et al. Robust Articulated-ICP for Real-Time Hand Tracking, Computer Graphics Forum. 34(5): 101-114,2015.
  25. Vlasic D, Peers P, Baran I, et al. Dynamic shape capture using multi-view photometric stereo. ACM Transactions on Graphics, 28(5),2009.
  26. Wang H, Sidorov K, Sandilands P, Komura T, "Harmonic Parameterization by Electrostatics" ACM Transactions on Graphics 32(5),2013.
  27. Wu C, Stoll C, Valgaerts L, et al. On-set performance capture of multiple actors with a stereo camera. ACM Transactions on Graphics, 32(6): 161,2013.
  28. Xu, W., Umetani, N., Chao, Q., Mao, J., Jin, X., & Tong, X. Sensitivity-optimized rigging for example-based real-time clothing synthesis. ACM Trans. Graph., 33(4), 2014.
  29. Yamazaki S, Kouchi M, Mochimaru M. Markerless landmark localization on body shape scans by non-rigid model fitting, Proceedings of the 2nd Digital human modeling symposium,2013.
  30. Zhang Z. Microsoft kinect sensor and its effect. IEEE Multimedia, 19(2): 4-10,2012.
  31. Zeng M, Zheng J, Cheng X, et al. Template-less quasi-rigid shape modeling with implicit loop-closure, Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, 145-152,2013.
  32. Zhang M, Lin L, Pan Z, et al. Topology-independent 3D garment fitting for virtual clothing, Multimedia Tools and Applications, 74(9): 3137-3153,2015.